Recording Brain Activity with Ear-Electroencephalography

Daniel Hölle[1], **Martin G. Bleichner**[1,2]

[1] Neurophysiology of Everyday Life Group, Department of Psychology, University of Oldenburg [2] Research Center for Neurosensory Science, University of Oldenburg

Corresponding Author

Martin G. Bleichner
martin.georg.bleichner@uol.de

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Abstract

The c-grid (ear-electroencephalography, sold under the name cEEGrid) is an unobtrusive and comfortable electrode array that can be used for investigating brain activity after affixing around the ear. The c-grid is suitable for use outside of the laboratory for long durations, even for the whole day. Various cognitive processes can be studied using these grids, as shown by previous research, including research beyond the lab. To record high-quality ear-EEG data, careful preparation is necessary. In this protocol, we explain the steps needed for its successful implementation. First, how to test the functionality of the grid prior to a recording is shown. Second, a description is provided on how to prepare the participant and how to fit the c-grid, which is the most important step for recording high-quality data. Third, an outline is provided on how to connect the grids to an amplifier and how to check the signal quality. In this protocol, we list best practice recommendations and tips that make c-grid recordings successful. If researchers follow this protocol, they are comprehensively equipped for experimenting with the c-grid both in and beyond the lab.

Introduction

With mobile ear-electroencephalography (EEG), brain activity can be recorded in everyday life, and new insights into neural processing beyond the lab can be gained[1]. To be suitable for everyday life, a mobile ear-EEG system should be transparent, unobtrusive, easy to use, motion-tolerant, and comfortable to wear even for several hours[2]. The c-grid (sold under the name cEEGrid), a c-shaped ear-EEG system, aims to meet these requirements to minimize interference with natural behavior. The grid consists of 10 Ag/AgCl electrodes printed on Flexprint material[3]. Combined with a miniaturized, mobile amplifier and a smartphone for data acquisition[4,5], these grids can be used to collect ear-EEG data for more than 8 hours[1,6].

Several studies conducted in the lab have shown the potential of c-grids for studying auditory and other cognitive processes. C-grids have been successfully used for auditory attention decoding with accuracies above chance level[7,8,9,10,11]. Segaert et al.[12] used these arrays to quantify language impairment in patients with mild cognitive impairment. Garrett et al.[13] showed that these arrays can capture auditory brain potentials originating from the brain stem. Apart from the research focusing on the auditory domain, Knierim et al.[14] used the grids to investigate flow experiences (i.e., the sensation of total involvement in a task), as measured by changes in alpha power. Finally, Pacharra et al.[15] used these grids for a visual task. All of these lab-based studies showcase the various cognitive processes that can be captured with these grids.

These grids can also be used for EEG recordings beyond the lab, as illustrated by several studies. For example, these arrays have been used to evaluate mental load in a driving simulator[16,17] and to study inattentional deafness, the non-perception of critical alarm sounds, in a flight simulator[18]. The grids are especially promising for long-term recordings, such as the long-term monitoring of epileptic seizures[2] and sleep staging[6]. Hölle et al.[1] used these grids to measure auditory attention during an office day for 6 hours. In sum, all of these studies highlight their potential to investigate various brain processes in and outside of the lab.

Every EEG recording requires careful preparation to obtain valid results. This is especially important for mobile applications where more artifacts can be expected than in the lab due to the movement of the participant. To ensure optimal results, specific preparation steps are necessary. We state the critical steps in preparing the grids, preparing the participant for data collection, and fitting and connecting the grids for EEG recordings. We point out potential mistakes and show examples of poor data quality when the attachment is not proper. Finally, representative results of a piano-played oddball task are shown.

Protocol

The general procedure used in this protocol was approved by the ethics board of the University of Oldenburg. The participant provided written informed consent prior to their participation.

NOTE: The c-grids should only be used on undamaged skin and with participants that do not have an allergy to the adhesive used. It has two sides. There is black text on the outside. The conductive surfaces of the electrodes are on the inside, and they face the skin of the participant during the recording. Importantly, handle these grids with care. Do not touch the conductive surfaces, do not fold the grids, do not excessively bend them, and avoid pulling on them.

1. Testing

NOTE: If handled with care, c-grids can be reused several times. To ensure optimal functioning, check that all the electrodes are working properly before the next recording. Perform the same procedure for new grids to identify potential problems (e.g., due to problems in the manufacturing process) before the recording starts. There are several options to quickly check for problems (e.g., a broken electrode).

1. Option 1: Multimeter.
    1. Set a multimeter to measure resistance.
    2. Attach one pin of the multimeter to the electrode and the other pin to the corresponding contact on the connector end.
    3. Check if a low resistance (<10 kΩ) can be measured for each electrode.
2. Option 2: Electrode gel

1. Use electrode gel to bridge all the electrodes. Make sure that there are no gaps between the electrodes.
2. Attach the grid to the connector of an amplifier. To see a signal, attach the grid to the side with the reference and ground electrodes according to the connector layout that is used.
3. Use the impedance check of the amplifier. Check the impedance of the reference electrode and all eight recording electrodes (10 electrodes in total minus the ground and reference electrodes); they must all have a low impedance (<10 kΩ). Afterward, wipe off the gel.

3. Option 3: Water

NOTE: Use this option with caution in order to not cause any water damage to the equipment.

1. Submerge all the electrodes in a glass of water, but make sure to keep the tail of the grid dry. Alternatively, place the c-grid in a plate filled with water (with the electrodes facing the plate).
2. Attach the grid to the connector of the amplifier.
3. Use the impedance check of the amplifier. Check the impedance of the reference electrode and all eight recording electrodes (10 electrodes in total minus the ground and reference electrodes); they must all have a low impedance (<10 kΩ). Afterward, dry the c-grid with a tissue.

2. Preparing the participant

NOTE: For high-quality recordings, the participant should have clean and dry hair, should not have used any hair products (e.g., styling products) or skin products, and should not be wearing make-up. If possible, the participants should wash their hair directly before the recording with a mild and neutral shampoo and also wash the areas around the ears. Ask the participants to indicate if any of the preparatory steps are uncomfortable for them.

1. To prepare the participant, the experimenter needs access to the area behind and around the ear. For participants with longer hair, use hair clips for easier access.
2. Place a c-grid around the participant's ear to see how it fits. Additionally, check if it can be positioned around the ear without touching the ear. Ensure it does not touch the back of the ear or the ear lobe, as this can be uncomfortable after some time. This pre-fitting also gives an indication of the area that will be covered and, thus, needs to be cleaned.
   NOTE: These grids come in one size and do not fit all ear sizes. For larger ears, cut some of the plastic around the electrodes on the inside of the C with a small pair of scissors. Pay special attention to not cut into the electrodes or the conductive path.
3. Apply a small drop of abrasive electrode gel onto a tissue. Use the gel to clean the skin around the participant's ear with some pressure, but make sure it remains comfortable for the participant. Make sure to generously clean the whole area that will be covered.
4. Dip a tissue in some alcohol, and clean the area behind the ear with this tissue.
5. Dry the cleaned area with a clean towel.
6. For higher levels of comfort, optionally place a small piece of tape on the back side of the ear.
7. Repeat all of the above steps (steps 2.1-2.5) for the other ear.

3. Preparing and fitting the grids

NOTE: There are different ways of attaching the c-grid using double-sided tape. Presented here are two options: c-shaped stickers (provided by the manufacturer) that cover the whole surface and small circular stickers that are placed individually around the electrodes (e.g., when reusing).

1. Attach double-sided adhesive stickers (either the c-shaped or individual stickers) around each electrode. Make sure that the stickers do not cover the conductive surface of the electrodes.
2. Put small drops (lentil-sized) of electrode gel on each electrode. Avoid using too much gel, as this might spill onto the adhesive material and reduce the adhesion to the skin. Too much gel could also create bridges between the electrodes.
3. Remove the cover of the adhesive sticker(s). Reapply the gel in case it was removed during this step. Alternatively, remove the first cover, and apply the gel then; however, this requires a very steady hand so the gel does not spill accidently onto the adhesive.
4. Ask the participant to hold their hair away from the ear so that it does not obstruct the fitting. Move any hair out of the way as much as possible so that the stickers touch the skin directly. Depending on the hairline, this is not always possible (e.g., when there is hair directly above the ear).
5. Position the grid around the ear, and when in place, press it into the skin. Make sure to not place it too close to the ear, as this may become uncomfortable for the participant. Leave some space (1 mm to 2 mm) between the grid and the back side of the ear. Additionally, ask the participant to press onto the electrodes.
6. Repeat all of the above steps (steps 3.1-3.5) for the other ear.
7. Remove any hair clips. Carefully place glasses or the strips of facial masks on the ears if necessary.

4. Connecting

1. Connect the connector to the amplifier. During this step, avoid excessively bending or pulling on the c-grid.
2. Plug the contacts into the connector. Make sure that the contacts are plugged in on the correct side. Ensure that the exposed contacts on the inside of the c-grid face the contacts in the connector.
   NOTE: It is important to know the layout of the connector being used (including the position of the ground and the reference electrodes). Depending on the system being used, the layout may differ. To build a connector, visit https://uol.de/psychologie/abteilungen/ceegrid. With the right connector, c-grids can be connected to any amplifier.
3. To hold the amplifier in place, use a headband, for example, to fixate it on the head.
   NOTE: The Oldenburg lab uses an amplifier that is built into a neck speaker called nEEGlace. The nEEGlace makes the setup more comfortable and faster.

5. Check the impedance and data

1. Connect the amplifier to a smartphone (optionally: a laptop) *via* Bluetooth.
2. Check the impedance of the electrodes with the impedance check of the amplifier. The impedance usually improves over time (5 min to 10 min) and does not have to be below 10 kΩ for each electrode in

the beginning. Do not try to put more gel underneath electrodes with a high impedance.

3. Check the EEG signal. Ask the participant to clench their jaws, to blink, and to close their eyes (alpha activity). Observe the corresponding artifacts and alpha activity in the signal. Make sure every electrode provides a good signal. If the resulting EEG signal is poor, remove the grid, wipe off any residual gel around the ear of the participant, and fit a new one.
4. Begin recording.

6. Removing and cleaning up

1. After finishing the data recording, disconnect the phone (or laptop) from the amplifier. Detach the grids from the amplifier, and remove the amplifier from the participant. Gently remove the c-grids from the participant. Make sure to neither bend the c-grid too much nor to pull out the hair of the participant. Allow the participants to clean themselves with tissues or a towel.
2. Soak the grids in water for some minutes. They can be submerged completely.
3. Carefully detach the stickers to avoid damage. Rinse off any remaining gel. Air-dry the grids. Do not rub over the conductive surface of the electrodes.
4. Store the c-grids safely in a dark and dry place.

Representative Results

When following this protocol, the impedance of each electrode is usually below 10 kΩ or approaches this value a few minutes after placing the grid (**Figure 1**), indicating a good electrode-skin contact. Of note, the impedance may still improve within 2 h after fitting it.

Figure 2 illustrates different unprocessed EEG signals. **Figure 2A** illustrates how the data looks when no gel is used. A conductive gel is required, and the grid does not work properly without using gel. If too much gel is used, the electrodes might be bridged. The data for this scenario are shown in **Figure 2B**. Bridged electrodes show exactly the same signal. When the preparation and fitting are carried out carefully, one can expect high-quality data, as displayed in **Figure 2C**.

Figure 3 illustrates the procedure and data from an exemplary event-related potential (ERP) paradigm (oddball task) with one participant. **Figure 3A** illustrates the paradigm. Specifically, the experimenter played a predefined sequence of two different notes on the piano (middle C and middle G). Middle C was played frequently (328 times), and middle G was played infrequently (78 times); the participant had to count the infrequent notes. The open-source AFEx app recorded the tone onsets, loudness (RMS), and spectral content (PSD) for all the tones. The Record-A app concurrently recorded the acoustic features and EEG[4]. In the analyses, infrequent and frequent tones were differentiated based on the power spectral density (PSD; see Hölle et al.[19] for details). The EEG data were high-pass filtered at 0.1 Hz and low-pass filtered at 25 Hz. A spatial filter was computed by using generalized eigenvector decomposition, which maximizes the signal of interest[20]. In **Figure 3B,C**, the resulting ERP with typical components of auditory processing can be observed, such as the N1 for both tones and the P3 for the infrequent tone that had to be counted. These results are consistent with previous oddball studies both with c-grids[1,3] and with cap-EEG[21,22].

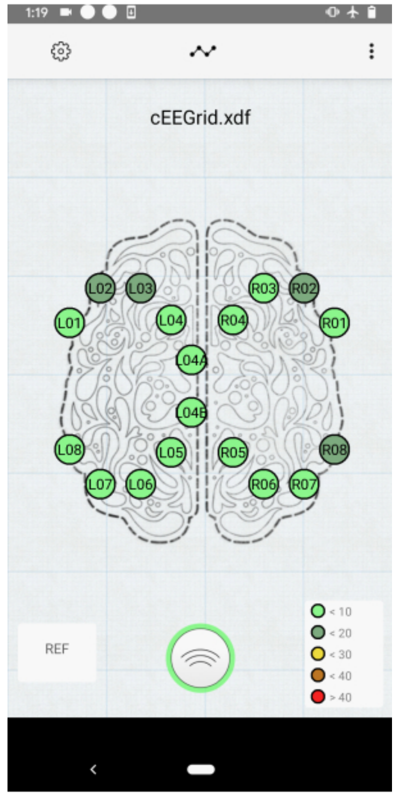

Figure 1: Example of good impedance. All values are in kiloohms (kΩ). Please click here to view a larger version of this figure.

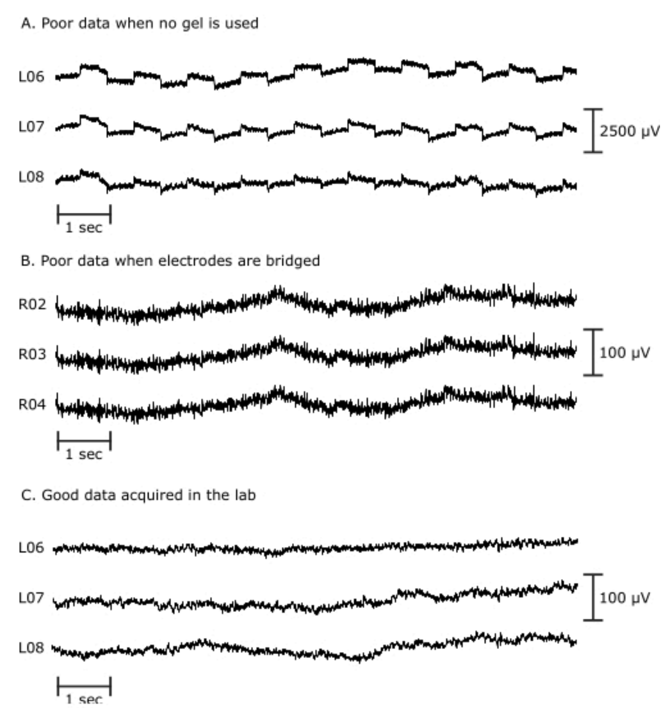

Figure 2: Illustration of unprocessed signals with different qualities. (**A**) Example of 10 s of data when no electrode gel is used at all. (**B**) Example of 10 s of data when the electrodes are bridged. (**C**) Example of 10 s of good data acquired in the lab. Please click here to view a larger version of this figure.

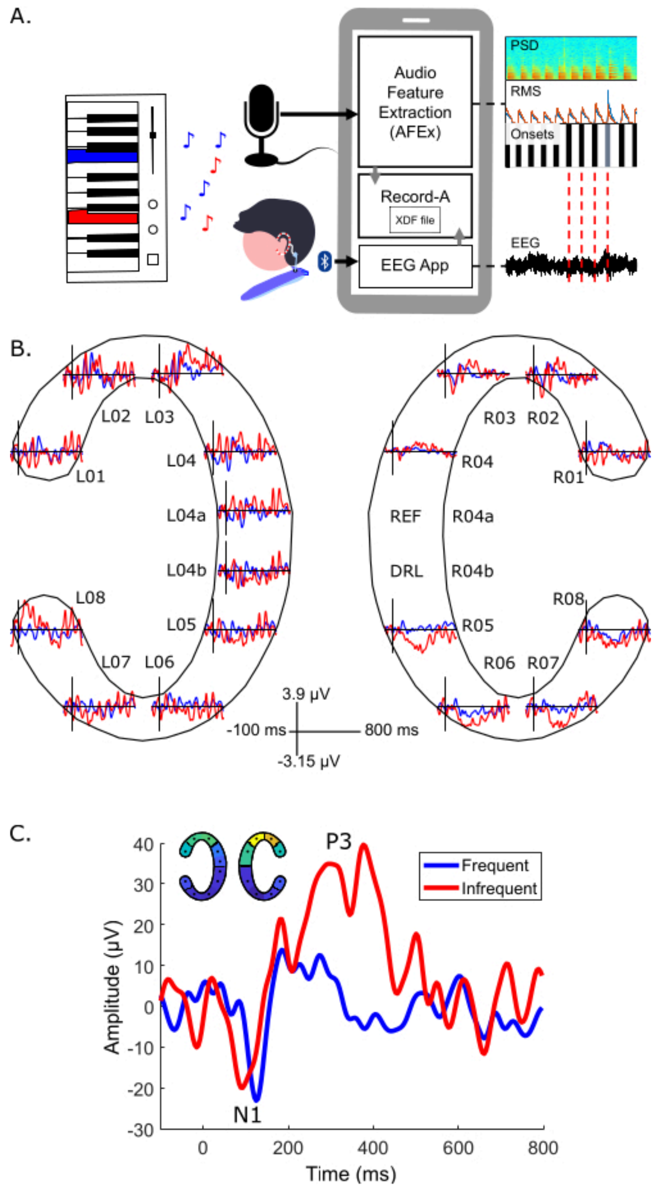

Figure 3: Results from an event-related potential (ERP) paradigm (oddball task) with one participant. (**A**) Overview of the paradigm. The participant listened to a sequence of tones played on a piano and had to count the infrequent one. The smartphone concurrently recorded the EEG and acoustic features (**B**) ERPs of all the c-grid channels. Abbreviations: REF = reference electrode; DRL = ground electrode. (**C**) ERP based on the spatial filter displayed in the top-left corner. Please click here to view a larger version of this figure.

Discussion

Provided here is a protocol for ear-EEG recordings with the c-grids. Following the steps of this protocol ensures high-quality recordings. In the following paragraphs, a comparison is made with cap-EEG, the most critical steps in the protocol along with some best practice recommendations are discussed, and some modifications are discussed.

Comparison of c-grids to cap-EEG and in-ear EEG

The c-grid allows the unobtrusive recording of brain activity in everyday life settings and is well suited for longer recordings. It has several advantages compared to cap-EEG. First, due to its weight, comfort, and low visibility, it barely restricts participants in their everyday activities[1]. Second, it can be worn for extended periods of time - more than 11 hours in one study[6] - without the electrodes falling off[1,3,6], since they are sealed by the adhesive stickers. On the downside, the c-grid covers only a fraction of the surface of cap-EEG and, thus, cannot replace cap-EEG for all purposes. However, in cases when a lightweight, unobtrusive, quick-to-setup, minimally restricting solution is necessary (e.g., in the workplace), c-grids can provide relevant neural information.

The comparison of results across participants is potentially more difficult for c-grids compared to cap-EEG. For cap-EEG, often the international 10-20 system is used to facilitate the comparison of results across studies and across participants with different head sizes. In this system, the electrodes are positioned relative to specific anatomical landmarks (i.e., the nasion and inion for front to back and the ears for left to right). In practice, different cap sizes are used to account for different head sizes and thereby approximate the optimal electrode positioning. The c-grid cannot be easily integrated into that system for two reasons. First, these are currently available in one size and, thus, cover more or less space depending on the head size. Second, the shape of the ear influences the positioning of the grids. In general, the two top-most electrodes will be directly above the ear, but depending on the ear shape, they might be tilted more to the front or to the back. We are not aware of any study that has investigated whether these shifts in electrode positions are large enough to be of relevance.

Another approach to measuring ear-EEG is to place the electrodes inside the ear, for instance, in the outer ear canal or the concha[23,24,25]. Such an approach offers even lower visibility than the c-grid but leads to recording signals with lower amplitudes due to the small distances between the electrodes[26].

Most critical steps

EEG in general, and especially mobile ear-centered EEG, remains a challenging technology. Therefore, the careful preparation of the participant and placement of the grids is essential to ensure good data quality over time. The preparation starts with the hair and the skin of the participants. The hair and skin around the ear should be washed and dried. In addition to that, the experimenter needs to carefully clean the area around the ear with abrasive gel and alcohol and ensure that the grids are firmly attached with the adhesive stickers. These steps are important and should be performed carefully to ensure good electrode-skin adhesion and a low impedance for longer periods. The skin cleaning especially can make the difference between a successful and an unsuccessful recording.

Even with proper care, however, the impedance for individual electrodes may still be poor directly after the placement of the electrodes. In general, the electrode-skin interface stabilizes over time, and we often observe that the impedance decreases within 5 min to 15 min. If the signal quality remains poor, it is recommended to completely remove the grids, wipe off any residual gel around the participant's ear, and fit a new one. It is faster to fit a new one as opposed to cleaning and preparing the previously removed grid. It is not recommended to add electrode gel to individual electrodes once the grid is fitted as this can compromise the adhesion strength of the stickers and can even lead to the bridging of the neighboring electrodes.

After the grid has been placed and when the impedance of the electrodes is low, data recording can begin. For longer recordings (>1 h), a brief data quality check should be conducted at the beginning. For instance, a 3 min auditory oddball task is exemplified in this study, which can be conducted and analyzed quickly to ensure a good signal quality.

In some cases, recording with the c-grid might not be possible at all, such as when the grid is too small for the ear (even after cutting) or when the hairline is too close to the ear, meaning that the grid does not stick to the skin. If the grid "hovers" over some hair, researchers cannot expect high-quality data.

Troubleshooting

Bad impedance and/or signal

To avoid these problems, it is imperative that the skin is carefully cleaned before fitting. Additionally, one should make sure to test the functionality of each electrode before the fitting. For example, one should check that the grid is plugged in correctly into the connector and that each electrode has firm contact with the skin and then wait for a few minutes until the impedance and the signal improve. To further check the functionality after fitting, the individual electrodes should be pressed, and the resulting signal should be checked. If the corresponding signal of each electrode shows a response, the electrode is functional in principle. If all of the above steps do not help, one should remove the grid, wipe off the residual gel around the participant's ear, and fit a new one.

Situations with no signal

Firstly, one should make sure the grid is connected properly to the amplifier, as well as ensuring that the grid connector is not upside down. There will be a signal only if the ground and reference electrodes are connected; whether the ground and reference will be on the left, the right, or on both sides depends on the connector.

Signal getting worse during the recording

There may be several reasons for this issue that need to be addressed. First, some of the electrodes might have become detached from the skin. This can happen when the adhesive is compromised by the remains of the electrode gel, by hair under the electrodes, or due to interference from the participant (e.g., scratching around the ear or adjusting glasses). Second, there might be problems with the connection between the grid and the amplifier (i.e., the grid might have been pulled out of the amplifier, or its position might have shifted). Finally, the grid might have sustained damage during usage. This can happen if the tail of the c-grid is bent too strongly.

Channels showing identical signals

In this case, the electrodes are bridged. One should remove the grid, wipe off the residual gel around the participant's ear, and fit a new one. One should also make sure to only use lentil-sized drops of electrode gel on each electrode to avoid bridging.

Participants reporting that the placement is uncomfortable

The most common reason for decreased comfort is that the grid is placed too close to the backside of the ear. One should make sure to leave 1 mm to 2 mm between the c-grid and the back side of the ear. A small piece of tape attached behind the ear helps to increase comfort.

Modifications of the method

The c-grid comes in one size. However, it allows for some flexibility regarding its size. By cutting the plastic of the inner side, the size may be reduced to fit larger ears. One should pay special attention in order to not cut into the electrodes or the conductive paths.

Depending on the amplifier used and the recording scenario, there are different ways to place the amplifier on the body. The fixed length of the tail of the grid and the fact that it points horizontally away from the ear limits the possible locations for placing the connector of the amplifier. Different manufacturers provide adapter cables that connect the grid to a specific amplifier (either mobile or lab-based). Different solutions have been proposed for placing the amplifier; some researchers use a headband[3], whereas others integrate it into a basecap[27]. For shorter experiments, a headband is suitable. For longer experiments, the amplifier can be taped to the clothes[6] or body[2], stored in custom-made straps, taped to headphones worn around the neck[1], or taped to a neck protector commonly used for mountain biking. We have developed a prototype that combines a neck speaker (for presenting auditory stimuli) with a mobile EEG amplifier and connectors to the c-grid (building instructions can be found here: https://github.com/mgbleichner/nEEGlace). We have used this approach successfully in a recent study (in preparation) in which we recorded ear-EEG for 4 h while participants worked in an office.

Future applications

The c-grid is a promising tool for long-term recordings in everyday life. For instance, one can use it to investigate sound processing in everyday life[1]. With long-term recordings, circadian variations in cognition and auditory function can also be investigated[28,29]. For diagnostic purposes, the grid can be used for the long-term monitoring of epileptic seizures[2], sleep staging[6], or for measuring attention for hearing devices[7,11].

Conclusion

This protocol comprehensively equips researchers for experimenting with these c-grids in and beyond the lab. If researchers follow this protocol and carefully perform the steps, including the most important ones, such as skin cleaning and fitting the c-grid, they can expect high-quality data for their ear-EEG experiments.

Disclosures

The authors report no conflicts of interest.

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