HARDWARE METAPAPER

Building an Ear-EEG System by Hacking a Commercial Neck Speaker and a Commercial EEG Amplifier to Record Brain Activity Beyond the Lab

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Electroencephalography (EEG) allows measuring human brain activity for scientific, diagnostic and therapeutic purposes. For scientific purposes, EEG is traditionally used to study the brain-behaviour relationship under well controlled laboratory conditions while the participant sits quietly in a room. Consequently, our knowledge regarding the brain-behaviour relationship was limited to human behaviour under constrained conditions. The development of mobile EEG hardware in the last years allows moving beyond the lab and studying brain activity in everyday life.

Most EEG systems record from electrodes that are distributed over the head, kept in place with an elastic cap or net. For long term EEG recordings, to study natural behaviour in public, these systems are not optimal, as they are rather bulky and unpleasant to wear for longer periods. We argue for “transparent”, ear-centered EEG systems instead. Transparent in the sense that both the person wearing the EEG system as well as the people interacting with that person are not disturbed by it.

We describe here the integration of a commercially available research-grade mobile EEG amplifier and a commercially available neck speaker as a mounting system to be used in combination with ear electrodes (cEEG-Grid). This nEEGlace can be used for ear-EEG recordings in public over extended periods of time. The integrated microphone and the integrated speakers provide the possibility to play and record sound. This allows conducting experiments on auditory perception beyond the lab by both studying the brain responses to naturally occurring sounds as well as to experimental auditory stimuli.

We describe the general design, present a working prototype, outline a number of use cases and discuss future improvements of the proposed design.

Keywords: electroencephalography; ear-EEG; mobile EEG; transparent EEG, beyond-the-lab experimentation

Metadata Overview

- Main design files: https://github.com/mgbleichner/nEEGlace
- Target group: neuro psychologists, neuro scientists
- Skills required: advanced soldering skills, basic skills in using precision screw drivers and power tools for cutting.
- See section (4) Build Details for more detail.

(1) Overview

Introduction

The understanding of pathological and non-pathological brain functions in humans relies on in-vivo recordings of brain activity using electroencephalography (EEG), functional magnetic resonance imaging (fMRI), magnetoencephalography (MEG), positron emission tomography (PET), and functional near-infrared spectroscopy (fNIRS). These methods allow studying the physiological basis of human cognition.

However, most of what we know about human brain functions, we learned from immobilized participants. As the different brain recording techniques are all highly sensitive to signal disturbances due to body movements, participants either sit or lie down and are asked to move as little as possible during an experiment. This means that we neglect brain functions during motion and during natural behaviour due to the technical limitations of these brain recording techniques.

It has become increasingly clear that there are differences in brain function during rest and during motion. Oppezzo and Schwartz (2014) show, for example, that we tend to be more creative while we walk. In the last years the new field of mobile cognitive neuroscience, looking into the underlying neural mechanisms, is emerging (Debener, Minow, Emkes, Gandras, & De Vos, 2012; Gramann, 2011,
2014; Gramann, Jung, Ferris, Lin, & Makeig, 2014; Ladouce, Donaldson, Dudchenko, & Ietswaart, 2017). This interest in mobile cognition is paralleled by technical advances in brain recording techniques. New mobile brain recording hardware allows leaving the classical lab setup and studying brain functions during motion or in everyday situations. The increasing interest in these questions, on the other hand, accelerates the development of new hardware.

Mobile EEG stands at the forefront of this development. Unlike fMRI, MEG or PET, EEG can easily be made portable and even wearable. EEG measures the electrical activity of groups of neurons using electrodes positioned on the scalp and a signal amplifier. Small, lightweight, mobile EEG amplifiers allow recording EEG virtually anywhere, for example during bungee jumping (Nann, Cohen, Deecke, & Soekadar, 2019). Mobile EEG setups generally consist of a cap with integrated electrodes (Figure 1A), a mobile amplifier, and a laptop or a smartphone which is used for data acquisition and stimulus presentation, e.g. for presenting experimental stimuli such as sounds or images (Bleichner & Debener, 2017).

For long-term EEG recordings in public we envision ‘transparent EEG’ (Bleichner & Debener, 2017). Transparent in the sense that neither the wearers nor their interaction partners notice the recording device. The wearers can forget about the device and behave as naturally as possible. The classical EEG cap, which is used in many mobile EEG setups is not optimal for long term EEG recordings in public. EEG caps pose several constraints on the duration, comfort and naturalness of the recording. First, EEG caps are often unpleasant to wear over extended periods of time. Second, the conductive gel which is necessary for a good skin electrode contact gradually dries out and leads to a reduction in signal quality over time. Dry electrode systems exist, but have an inferior signal quality (Radüntz, 2018) and are even more susceptible to movement artifacts. Third, EEG caps may alter the behaviour of participants, e.g. by making them insecure about their appearance. As a consequence, participants may avoid certain social situations and thereby change their normal behaviour. Finally, caps may change the reactions of others towards the participant (i.e. making a natural interaction less likely). While this may be tolerable in many research contexts, it is problematic for long term recordings in everyday situations.

For our use cases, the EEG amplifier as well as the EEG sensors should be disguised or hidden from view as much as possible (Figure 1B), but should still allow recording the

Figure 1: A) Mobile EEG setup using an electrode cap. The recordings electrodes (red) are distributed over the scalp and are kept in place by an elastic cap that is secured in place with a strap under the chin. The EEG amplifier is attached to the back of the cap. The smartphone, that is used for stimulus presentation and data acquisition, is attached with a pouch on the upper arm. The communication between smartphone and amplifier runs via Bluetooth. Audio stimulation is done via in-ear headphones. B) Mobile nEEGlace setup using cEEGrids. The cEEGrids are connected to the nEEGlace with connector cable (light blue) that sticks out of the neck piece. The mobile amplifier is integrated into the neck piece. The data acquisition is done on the smartphone the communication between smartphone and amplifier runs via Bluetooth. Audio stimulation and audio recording is done via the neck speaker that is connected with a cinch-cinch cable (white) with the smartphone.
brain processes of interest. These two criteria are difficult to satisfy simultaneously. On the one hand, the best system to record brain activity would have a large number of electrodes, widely distributed over the head. However, to keep the electrodes in place, some kind of net or cap is needed, which tends to be very noticeable. Some attempts were made to hide tiny electrodes in the hair (Nikulin, Kegeles, & Curio, 2010), but the problem of keeping those electrodes in place comfortably and inconspicuously remains.

On the other hand, the most disguised system would not be noticeable at all. Consequently, such a system would only record from a limited number of electrodes and therefore would only be sensitive to a limited amount of brain processes (Meiser, Tadel, Debener, & Bleichner, 2020).

We argue that in-ear (Kidmose, Looney, Ungstrup, Rank, & Mandic, 2013; Looney et al., 2011) and especially around-ear (Debener, Emkes, De Vos, & Bleichner, 2015) EEG solutions provide a satisfactory compromise. Ear-EEGs are inconspicuous enough to be used in public and are sensitive to a variety of neuronal signals (Bleichner & Debener, 2017; Bleichner, Mirkovic, & Debener, 2016; Debener et al., 2015; Denk et al., 2018; Mirkovic, Bleichner, De Vos, & Debener, 2016), not limited to, but especially to those that originate in the temporal cortex (Meiser et al., 2020).

Ear electrodes can stay in place for long periods of time or be re-positioned accurately (e.g. individualized ear-molds for in-ear EEG), which allows for constant recording conditions.

In a feasibility study (Hölle, Meekes, & Bleichner, 2020), we combined a mobile EEG amplifier, with ear electrodes, attached to a pair of headphones worn around the neck (used to play sounds) to record EEG for an entire workday. We showed that the recorded brain data was of sufficient quality to study auditory attention. For that study we combined several hardware parts as there was no commercial EEG system available that fulfilled our requirements. We found that participants tolerated the setup well and could do their normal office work during the recording. However, that study also made clear that the used setup was far from optimal, both in regard to user comfort and visibility.

Here we present a more integrated prototype that solves some of these issues. We designed a research-grade EEG setup that is sufficiently inconspicuous to allow for EEG recording in everyday situations, the nEEGlace (Figure 2). For this we integrated mobile EEG hardware into a neck speaker (i.e. a consumer product to play music similar to a headphone; the speakers are integrated into a neck piece which is worn around the neck, the ears remain uncovered) and combined it with ear-EEG electrodes (cEEGrids).

This EEG setup uses smartphone based signal acquisition and allows for stimulus presentation (audio) and sound recording.

**Overall Implementation and Design**

The nEEGlace consists of three components that are combined into a single neck set: a neck speaker\(^1\), an EEG amplifier, and a connector to connect to cEEGrid\(^2\) electrodes (around-the-ear sensor array).

The neck speaker serves as a mount for the amplifier and brings the cEEGrid connectors close to the ears. The speaker also allows playing back sounds, an integrated microphone allows recording all sounds the person wearing the nEEGlace is currently exposed to.

For our design, parts of the neck speaker are removed to make room for the amplifier and the connectors. The original electrode connector of the amplifier is replaced by special cEEGrid connectors that are positioned close to the ears.

**Universality of the Design**

The idea of a neck piece to mount EEG hardware can be implemented in many different ways. The neck speaker can be replaced by another brand with a similar form factor, or be built from scratch (e.g. 3D printed). Any other kind of mobile amplifier could be used, if the specs of the specific device are suitable or at least sufficient for the research question. The same holds for the electrodes used.

**(2) Quality Control**

**Safety**

There are no specific risks anticipated for this design. All risks of the end product are already present for the sub-components in their original form as described below.

**EEG Amplifier**

EEG is a well-established technology to record brain activity non-invasively. It is considered safe, with no negative effects for the participants. The mobile

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**Figure 2:** nEEGlace for recording ear-EEG for extended periods in public. **A**) back view; **B**) front view; **C**) top view. The mobile EEG amplifier is integrated into the back part of the neck speaker where the battery of the neck speaker was located.
amplifiers used here are CE certified in their original form (however, all warranty is lost once it is altered in the way we describe here). If the modifications are done correctly we expect no problems. The largest safety risk is related to the batteries. The mobile amplifiers are powered by a lithium-ion battery. These batteries need to be handled with care. Batteries that are damaged during the assembly process must not be used. A damaged lithium-ion battery may cause short circuit, leading to a thermal runaway and a potential fire hazard. As stated in the user manual of thesmarting amplifier: the amplifier must not be used while charging!

**Neck Speaker** The neck speaker is a commercial product, and no additional risks due to the redesign are anticipated. Due to the removal of lithium-ion battery, any battery related risk is removed as well. The largest risk may be the sharp edges on the casing if the alterations are not done with care. This can easily be mitigated by working carefully, and filing off all problematic edges.

**Ear Electrodes** The cEEGrid electrodes are made from bio-compatible material and no negative side effects are known (Debener et al., 2015). The used electrodes are passive. The electrodes are placed with a double sided sticker to the skin. A bit of conductive gel is needed for a good electrode-skin contact. Sensitive people may experience allergic reactions to the glue or the conductive gel. For those cases, hypoallergenic alternatives are available.

**Connector Cables** The amplifier is connected to the cEEGrid with the connector cables and the cEEGrid’s tails are inserted into the connector. This connection is tight enough to keep the cEEGrids in place even during movements. However, the connection would come loose if there is either a strong pull on the cEEGrid or the connector cable (e.g. by fast, large head movements). In odd cases it could happen that this cable connection gets caught in something. In that case it may happen that the cEEGrid is pulled out of the connector, that the connector cable tears away from the amplifier, or the cEEGrids tick off the skin. This would lead to a damage of the hardware components or discomfort for the wearer, respectively.

The system is not splash water protected and cannot be used in water or during precipitation.

**General Testing**

The neck speaker, the EEG amplifier, and the ear electrodes are commercially available products. The functionalities of all sub components are well established and have been validated numerous times. Obviously, the dis- and reassembly for our purpose may compromise the functionality of any component. Before using this setup productively, one should run a couple of simple tests to assure the functionality of the system including the speakers and the microphones. One quick and easy test to see whether neurophysiological signals can be measured,
is to record from a person sitting quietly first with open and then with closed eyes for some minutes. Closing the eyes will lead to a characteristic change in the signal at around 10 Hz which is often large enough to be seen in the raw signal. This change in the 10 Hz range (so-called alpha band), is one of the largest and most robust effects that can be observed in EEG. The alpha activity increases when closing the eyes and decreases when opening the eyes. Figure 4 (A–D) shows the time line of the simple experiment and the expected outcome for a recording using the nEEGlace.

(3) Application
The nEEGlace in combination with ear-electrodes can be used to record neurophysiological data over extended periods of time in everyday situations. Its primary area of application is research. The neck piece and the electrodes around the ear are comfortable to wear and are not directly apparent to others. If you build this system yourself, it must not be used for clinical applications (in Europe, medical devices require CE-Marking to declare that the device is in compliance with all legal requirements of the European market. This is not the case for this device).

The setup of the system is simple and will not take longer than 5–10 minutes. First, the skin of the participant is prepared for electrode placement. For this the area around the ears is cleaned with alcohol wipes. Second, the cEEGrids are prepared. A bit of conductive gel is applied to each electrode. The cover of the pre-applied sticker is removed from the cEEGrid, and the cEEGrid is positioned around the ear. Third, the nEEGlace is placed around the neck. Fourth, the cEEGrids are connected to the nEEGlace by inserting the tail of each cEEGrid into the connector. If the audio capabilities of the nEEGlace should be used, a cinch-cinch audio cable can be used to connect the nEEGlace and the smartphone (or a laptop). Finally, the data transmission between amplifier and the recording program on the smartphone (or laptop, see section Operating Soft-ware and Peripherals) can be started and electrode impedance can be checked. The stimulus presentation and signal acquisition can be started.

A mobile recording can continue until the battery of the amplifier or the smartphone go flat. After the recordings, the electrodes can be disconnected from the connectors. The cEEGrids can be removed from the skin and the skin can be cleaned with tissue paper.

Figure 4: Simple validation experiment for the nEEGlace: A) Experimental Setup – With all nEEGlace components in place (see section (3) Application), sit quietly in a chair for four minutes, with either eyes open or eyes closed (60 seconds each, repeat twice). B) Time course – Single cEEGrid channel as recorded with the nEEGlace during the eye-open, eyes-closed experiment (channel R07). The data shown here is recorded from the first author. The signal is band-passed filtered (0.1 to 45 Hz). The resulting EEG signal fluctuates over time with an amplitude between –100 and 100 μV. C) Time course – Same data as in B) but filtered in the “alpha band” range (7 to 13 Hz). The clear increase in amplitude for the periods with closed eyes is readily apparent in the filtered signal (i.e., compare the first 60 seconds, with the second 60 seconds). D) Power spectra – Power spectra for each 60 sec period of eyes-open (first and third column) and eyes-closed (second and forth column). For the eyes-closed condition a large increase in power in the alpha range (10 Hz) compared to the eyes-open condition is evident.
Use Cases

Study of Natural Fluctuations in Brain Dynamics

EEG is suitable to study brain processes on several time scales – from brain processes that unfold within a few milliseconds, to brain processes that unfold over hours or even days (e.g. attention, fatigue, circadian rhythms, hormonal cycles). While fast brain dynamics can easily be studied in classical EEG recordings sessions, which do not last longer than 1–2 hours, slower brain dynamics are more difficult to study.

Lab recordings of more than 2–3 hours are very tiring to the participants. This makes it difficult to gather data that is representative of natural brain processes during daily life activities. The alternative, multiple shorter recordings which are spread out over the course of a day, has several problems as well. First, the necessary visits to the lab might already influence the brain processes of interest. Second, with standard EEG caps, the exact re-positioning of the electrodes is not possible. The individual recordings would therefore not directly be comparable with each other.

The nEEGlace is convenient to wear for long periods of time and the signal quality can be expected to be high throughout the recording. The ear-electrodes remain at the same spot and no re-attachment of the electrodes is necessary, assuring constant recording conditions. Previous studies have shown that the cEEGrids can be worn without discomfort for more than 8 hours and even during sleep (Bleichner & Debener, 2017). Though not fully transparent, participants can move more or less freely and engage in everyday activities. It is hence conceivable that brain activity can be recorded in different everyday situations and that naturally occurring brain dynamics can be studied more easily.

Sound Perception in Everyday Life

In our research, we are interested in sound perception in everyday life (Hölle et al., 2020). We want to understand how the brain processes naturally occurring sounds, and why we are disturbed by some sounds but not by others. Our sound sensitivity is situation dependent and varies over time. With EEG recordings in the lab we can only get snapshots of the brain activity. With the nEEGlace in combination with ear electrodes we can move beyond the lab and study sound perception in natural soundscapes. The recording functionality of the nEEGlace allows monitoring the existing soundscape. The playback functionality allows presenting experimental sound stimuli in addition to the naturally occurring sounds.

Reuse Potential and Adaptability

Our design has a high degree of adaptability. Different neck speakers and different EEG amplifiers could be used. Additional (bio-) sensors could be added to the neck piece for further sensing capabilities. Additional batteries could be added to extend the recording time. The build description can be found on GitHub (mbgleichner/nEEGlace). Others are free to fork from this project and add additional information or describe alternative approaches.

The nEEGlace could also be built using the open source EEG hardware components from the OpenBCP project.

(4) Build Details

Availability of Materials and Methods

The system is built from an EEG amplifier (Smarting, mBrainTrain, Belgrade, Serbia), a JBL neck speaker (JBL Soundgear BTA) and two cEEGrid connectors. The Smarting amplifier is commercially available from several specialised EEG resellers and from the manufacturer (www.mbraintrain.com). The JBL is commercially available online. The cEEGrid connectors are commercially available from different companies (e.g. www.tmsi.com).

The cEEGrid connectors are not commercially available, but need to be built from several components. The connector PCB is not commercially available. The PCB design is available online, we provide sources where the PCB can be produced (described in the main design files).

Ease of Build

The current design requires a considerable degree of dexterity, a fair understanding of electronics and good tools (rotary power tool, soldering iron, precision screw drivers, clamp, cutter knife, rasp/file, pliers). Parts of the neck speaker casing and of the amplifier casing need to be cut out. The original connector cables need to be soldered off of the amplifier board, the cEEGrid connectors need to be soldered onto the board of the amplifier. (Be aware that this step can permanently damage the amplifier if not done correctly! The authors of this article, are not responsible for any damage to your device. By following the steps in this document, you will lose all manufacturer warranty. Given the costs for the EEG amplifier, you should have some experience with all steps involved). For the rest, all necessary steps are relatively simple.

Operating Software and Peripherals

The Smarting amplifier comes with proprietary software for Windows and Android (see manufacturers website for details). For our work we use the Android version on a smartphone. We use the Smarting app to connect to the amplifier via Bluetooth, and store the EEG data on the smartphone. For our experiments we use proprietary software (Presentation, Neurobehavioural Systems) to present experimental stimuli (e.g. sounds) to assure high temporal precision (see Figure 3). We use a self-built app to record sound (which will be described elsewhere).

Open Source Alternatives

There are open source alternatives to the proprietary software we use for interfacing with the amplifier and for stimulus presentation. The Smarting amplifier works with OpenVibe which allows collecting EEG data. OpenVibe is an open source software (Windows, Linux) for brain computer interfaces and real time neuroscience (AGPL license). OpenVibe comes with an acquisition server to communicate with various hardware signal acquisition devices (including the Smarting amplifier) using hardware specific modules (drivers).

For stimulus presentation there are various open source alternatives. OpenSesame is a cross-platform (Windows, Mac OS, Linux and Android (runtime only)) python-based stimulus presentation software (GPL3 license). PsychoPy is a Python-based library for designing, delivering and recording data from experiments. It was created as an alternative to proprietary software such as E-Prime and PsychoLingua.
is another python-based, free, cross-platform package for implementing and running experiments (GNU GPL v3+ license). A third option is to use Psychotoolbox⁴, a toolbox for stimulus presentation for MATLAB and Octave.

**Necessary Parts**
- JBL Soundgear BTA¹
- Smar ting EEG Amplifier²
- cEEGrid connectors⁷
- Female Jack Plug Socket

**Hardware Documentation and Files Location**

*Name:* nEEGLace  
*Persistent identifier:* https://github.com/mgbleichner/nEEGLace  
*Licence:* The hardware design is licensed under the CERN Open Hardware Licence Version 2 – Permissive  
*Publisher:* Martin G. Bleichner  
*Date published:* 2. July 2020.

(5) Discussion

The nEEGLace combines a neck speaker with a mobile EEG amplifier and connectors for around the ear electrodes (cEEGrid). The nEEGLace can be used to record brain activity and for presenting and recording sound in the lab and beyond. The integrated gyroscopes of the EEG amplifier allow capturing some movement parameters of the wearer. We present this prototype to motivate others who are more technically inclined and who have access to better production facilities to develop and construct a dedicated nEEGLace.

This version is a combination of existing, commercially available elements, a hardware hack. Initial tests with this setup show that it is functional both for recording brain activity as well as for presenting and recording sound.

There are numerous ways to improve the current design as we point out in detail below. A dedicated development of the nEEGLace from scratch would allow optimizing all components. The goal is to have a robust and easy to use research platform for ear-EEG recordings beyond the lab in everyday life.

**Future Improvement**

**Dedicated Neck Piece**

A dedicated neck piece should provide sufficient room for all necessary parts, sufficient battery capacity (>8 h, or should be quickly rechargeable), good sound quality and high user comfort. It should be robust enough to be used continuously outside the lab without supervision of an experimenter.

The neck piece should have a snug fit around the neck to reduce any movement of the device around the neck, and to prevent the loss of the neck piece during movement. Furthermore, special attention needs to be put into assuring a light-weight design with a balanced weight distribution to maximise wearing comfort during long term usage.

Furthermore, a dedicated design should pay attention to the audio quality. For our prototype we may have compromised the audio quality by opening up the neck speaker, cutting into it and by removing some parts of the hardware (battery as well as control electronics). This may have potentially negative effects on the sound quality of the neck speaker due to less resonance space and rattling due to insufficiently fixed parts (we did not observe any of these effects for our prototype).

Overall, the product quality needs to be improved. This includes a (water-tight) housing that protects the amplifier hardware (at least from mild rainfall). The cEEGrid connectors need to be soft and flexible enough to allow for undisturbed movement of the participant but robust enough to withstand some strain (e.g. due to sudden large head movements). Ideally, the entire neck piece would be robust enough to withstand careless treatment (i.e. flung on a table) to accommodate at-home usage without experimenter supervision. Protruding parts, (i.e. the amplifier in our design), should be avoided in this regard as well.

**Additional Sensors**

Our prototype allows playing and recording sound. In the current version the sound recording is mono, with a microphone on one side only. Future developments should have at least one stereo microphone (preferably more), to record the natural soundscape surrounding the participant, in order to relate the soundscape to the ongoing EEG. In order to comply with European privacy protection laws, which do not allow recording other people in public, it is necessary to store the audio in such a way that the content of conversations or the identity of a person is protected. There are smartphone based audio recording solutions that allow this by only storing some audio features (Bitzer, Kiss, & Holube, 2016; Kowalk, Kissner, von Gablenz, Holube, & Bitzer, 2018).

The Smarting amplifier we used is equipped with a gyroscope to measure movement like most mobile amplifiers. By design this amplifier is intended to be used with an EEG cap and is attached to the back of the head in a pouch on the cap. In that case the gyroscope captures head movements in all directions (pitch, roll and yaw) very well. In the case of the nEEGLace, the gyroscopes are now located in the nEEGLace on the neck. This means that head movements are not necessarily captured if the shoulders with the nEEGLace remain still. Future designs should have additional motion sensors, e.g. attached on the cEEGrids to capture head movements. This movement information is not only necessary to know what a person is doing, but could also provide information about movement induced artifacts (e.g. due to electrode displacement due to head movement), and could consequently help with their removal (O’Regan & Marnane, 2013).

A dedicated neck piece could also mount numerous additional sensors. Depending on the use case a variety of sensors is conceivable, such as light and temperature sensors to get more information about the surrounding of the person.

**Fully Wireless**

The used Android software for the EEG amplifier does not allow to simultaneously use Bluetooth to receive EEG data from the amplifier and to transmit audio to the neck.
speaker. More importantly, we removed the Bluetooth functionality of the neck speaker as we removed the battery to make space for the amplifier. Therefore, our prototype requires a stereo cinch-cinch cable to record and play back sound. In future designs, all communication with the nEEGlace should be wireless, i.e. the transmission of all information to and from the nEEGlace should be based either on Bluetooth, WiFi or NFC (near-field-communication) under consideration of the amount of data that needs to be transmitted (both directions) and the expected drain on the battery. Furthermore, recharging should be induction based to avoid a connector socket (see section Battery).

**Data Storage or Data Transmission**

For mobile EEG systems, there is the design decision on where to store the data. The signal can either be transmitted to an extra recording device (here a smartphone) or stored locally on the EEG amplifier (e.g. on an SD-card). On-board recording has the advantage that no telemetry is necessary during the acquisition. This leads to longer battery life, reduces the risk of data loss due to transmission problems (e.g. due to other interfering devices), and is easier to implement. On the downside, on-board recording can make it more difficult to combine the EEG signal with other data streams (e.g. event marker). For example to add event markers, a marker signal would have to be recorded on the device itself requiring potentially further hard wire connections.

However, the synchronized acquisition of multiple data streams is essential for EEG recordings, especially for beyond the lab recordings. For EEG experiments it is necessary to relate the EEG signal to some stimulus (e.g. a visual or auditory event). For this we have to know when those stimuli occur relative to the EEG signal. For most of our mobile EEG studies we use the lab streaming layer framework (LSL) to integrate data streams from different devices. Lab streaming layer allows the synchronized acquisition of multiple data streams with different (even irregular) sampling rates. Each data sample receives a time stamp as early as possible. Future designs should consider to use LSL for data synchronization.

**Battery**

For beyond the lab recordings one would like to have a battery life of at least 8 hours (nine-to-five workday). The battery of the Smarting amplifier allows a recording time of 3–5 hours. The Smarting sleep amplifier has 15 hours of battery life, but it is considerably larger and cannot be integrated into the current neck piece due to the size of the battery pack. It is conceivable to have several smaller batteries integrated into the neck holder, e.g. at each side for balanced weight distribution (see above). Ideally, the battery would be charged by induction, as this would increase the longevity of the device for at home use.

**EEG Sensors**

The cEEGrid (Debener et al., 2015) is a research product to facilitate ear-EEG research. However, for long term recordings in public it is not ideal in terms of usability, re-usability and user comfort. Currently, it is necessary to apply a small amount of conductive gel to each electrode, what requires some training, and makes self-application difficult. Furthermore, cEEGrids come in one size only and do not fit all ears equally well, leading potentially to discomfort if used for longer periods.

The optimal ear-EEG sensors would be comfortable for wear for long periods of time and should not lead to skin irritations, even after repeated usage. They should be light-weight, robust and self-applicable. It should be easy to position and should allow for easy re-positioning at the same location.

**Choice of Amplifier**

We use a Smarting amplifier here as we have extensive experience with it and because it integrates into our experimental ecosystem (Blum et al., 2017). The form factor of the device is not ideal for the integration into the neck piece. In principle every other mobile amplifier would work. However, for applications using ear-EEG it needs to be assured that the amplifier is sufficiently sensitive to the small signal amplitudes that are measurable with electrodes around the ears. Depending on the origin of the measured signal the amplitudes recorded around the ear can be 10 times smaller compared to recordings with an EEG cap (Meiser et al., 2020). The neural signals of interest are tiny compared to other influences (e.g. due to muscle movements). The noise floor of many research grade amplifiers lies at around 1μV. The acquisition of high-quality EEG data requires high-quality EEG hardware. Good amplifiers are characterised by low input noise (i.e. ≥1μV), high-common mode rejection, high temporal precision (this includes reliable and continuous sampling, as well as the possibility to integrate trigger information with millisecond precision), the possibility to get the raw, unfiltered or otherwise pre-processed data and high quality electrodes. For our purpose we also need mobile storage capabilities or smartphone compatibility.

**Conclusion**

The here presented prototype of an ear-EEG system that can be worn around the neck, shows the general feasibility and practicality of such a system for beyond-the-lab EEG recordings. Dedicated future development is needed to turn this prototype into a commercial product or to make it a fully open hardware project to make it available to the research community.

**Notes**

1. https://www.jbl.com/bluetooth-speakers/JBL+SOUNDGEAR+BTA.html.
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Competing Interests
The authors have no competing interests to declare.

Author Contributions
Martin G. Bleichner conceived and designed the nEEGlace together with Reiner Emkes. Reiner Emkes assembled the hardware. Martin G. Bleichner evaluated the nEEGlace and wrote the manuscript.

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