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This work is a screenshot of the original work, which had the participation of Andrew Proudfoot, Layla Khalili, Nikita Zagorodski, as well as myself Mohamed Fouda.

The work below only highlights my contribution to the project.

Physical Design

In designing the electrode cap, it was decided that the biomedical characteristics of function of the cap was going to be a priority with human factors, such as comfort and fit, being a close second. Biomedical characteristics of the cap that determine function are the number, placements, types, and materials of the electrodes used. These factors, especially number and placement, were considered more in a biomedical lens, and narrowed considering human factors, such as comfort, in mind. There are multiple studies which tried to determine the most necessary combinations of placements to have in order to analyze desired motor or base needs. This is going to be crucial for a locked-in patient. It was important to narrow the number of electrodes that were necessary from a design perspective. This is because a lower number of electrodes would be preferred, as it would add flexibility in the size of the device for each electrode to properly touch the scalp, the maintenance of the device, the comfort of the patient, and not to mention decreasing the costs of production.

Electrode Placements and Number

After researching, it seemed the most common and necessary electrode placements for motor analysis were the Cz, C3, C4, F7, F8, AF3, AF4, T7, T8, P3, and P4 [24]. An idea we would like to explore is including at least one of the occipital electrodes, O1 or O2, in the design for testing purposes. This is an area we are curious to explore since locked-in patients typically will be able to see and interpret brain signals that account for the visual information that is being processed. This sets the max number of electrodes to be 12.

Electrode Type and Material

One design requirement that happened to be determined more by the weight of human factors than biomedical factors was the type of electrode. The type of electrode is defined by whether a coupling medium is used between the electrode and scalp. There are dry, semi-dry and wet electrodes, where dry has no coupling medium, and semi-dry and wet may have a coupling medium such as a gel or some other electrolytic liquid. Due to human factors, such as the consideration of comfort for the patient and maintenance done by the caregiver, it was decided that although including a wet electrode would give a better impedance and functional result. It seemed impractical considering it would be a device worn longer-term and daily by the patient, so the caregiver would have to reapply medium onto the cap, and the fact that the caregiver needs to place and remove the cap every morning and evening. Coincidentally, another paper mentioned that the use of a polymer electrode would be a promising alternative to the conventional gel electrodes. It provides the same impedance as a metal, gel electrode with more comfort [25].

Prototype Design

For the prototype design solution, the team began by brainstorming ideas and prototype requirements. After writing a list of about ten design ideas and requirements, the next step was to draw ideas to make a visual representation of them. Finally, building one or two of the prototypes that seemed to match the best with the requirements and other metrics was the final step. The prototypes are low fidelity due to the time constraints and other responsibilities of the team. A baseball cap and a headband with metal wires are the bases for the two EEG cap prototypes. Plastic buttons between 2-5mm [29] were used to represent electrodes, and string is used as wire to connect the electrodes, while the metal wires connecting some of the electrodes to the headband were used as a design inspired by the Emotiv EPOC headset.

Design Ideas:	Design Requirements:
A traditional headband	Size/circumference needs to be flexible or adjustable.
A traditional cap	Tightness needs to be adjustable or flexible.
A summer beanie (or a cap-less cap)	Needs to be non-alienating or does not stick out; or needs to stick out with a good/customizable design.
A summer beanie made of straws	Should have minimal volume to be very easy to clean.
Hair wig	Stays in place.
A hairclips sensor electrodes	Should have the comfort of cloth headwear, but the ease of maintenance / to clean of metal/hard material.
Glasses on top of head	Might be great not to cover the entirety of the head, so it doesn't get as dirty over long times OR good air flow / breathable.
Glasses on top of head	Sensor placements around the head
An electrode with chain jewelry on top	Electrodes should be comfy.
For kids, a boxing cap or an astronaut helmet or buzz light year	

Table 4 – Results from team brainstorming session to make two separate lists: design ideas and design requirements.

Analysis & Design Steps

- Step 1: what are the restrictions and boundaries in terms of sensors, and brain location, and other technical boundaries?
- Step 2: what are successful and examples of the four criteria we defined (fit comfort, ease of maintenance, friendliness "cool" factor, cleanliness for long wear) and create moodboard and assessments of what we define as successful examples/products
- Step 3: illustrating and brainstorming different ideas of our "product" solution
- Step 4: build a physical prototype.
- Step 5: (If enough time) user testing and interviewing. iterating on prototype. (If not enough time) next iteration steps and future path. User testing plan. ADDED: Recording a video of prototypes or illustrations, explaining the difference (like a user testing of a software UX)

Breakdown of Analysis & Design Steps

Step 1: How did we define the metrics (fit comfort, ease of maintenance, friendliness "cool" factor, cleanliness for long wear) that are important for ranting?

Due to the limited scope of this project, and how much "real" users we can interact with, the following was mostly based on online research.

The team looked first at the experience of locked-in patients in order to understand three aspects and get close to them as much as possible:
- The lived experiences of a locked-in syndrome patient,
- The lived experience of a caregiver for a locked-in syndrome patient
- The dynamic between the caregiver and the patient

The research had to be based on observational notes, which is one of the human factors research methods meant to understand the experience of a user in order to include it in the design process. This meant that the information gathered was mainly qualitative in nature and not quantitative, which meant the team had to devise a way to measure metrics based on these notes later on.

The four criteria that were identified based on the observed experiences were the following:

Long term fit comfort	Ease of maintenance for caregiver	Friendliness “cool” factor to a stranger	Long wear cleanliness

Long term fit comfort

One of the most important requirements for a product such as EEG which is to be worn on a user’s head, is the comfort level after being worn for a long time. This is especially important in the case of EEG and locked-in syndrome patients mainly for two reasons. The first, being that the task applications envisioned for the patient to perform based on the device are tasks that are classified as “natural extension” of a user (for example, moving limbs, communication, etc). Thus, since these tasks require the user to wear the device in order to perform them, and the tasks envisioned are ones that would drastically improve the quality of life for the patients, it is natural to assume that the device would be worn for long periods of time.

This time was assumed to be around 16 hours (which is the total average time a person is awake, assuming 8 hours of sleep). For the future, the team envisions this time to be extended for ~24 hours where the device could be worn even when the user is asleep.

Ease of maintenance for caregiver

Maintaining an EEG device, especially based on current products and the current designs, might prove to be tricky for a caregiver. This is due to the fact that it would add an extra burden on the already burdened caregivers’ tasks. In this case, it is assumed that a caregiver is one person (not a team or a group of people, based on observations from online lived experiences of caregivers for locked-in syndrome), and would be performing the tasks of maintenance to the device by themselves on top of the existing duties they have.

This maintenance includes the following tasks: charging the batteries / or replacing the batteries of the device, cleaning the electrodes, cleaning the overall of the device, removing the device for storage (at the end of the day), putting the device on the patient’s heads at the beginning of the day.

Long-term wear cleanliness (long-term lasting)

Besides the maintenance of the EEG device, another important requirement is the how often the device needs before it is considered “dirty” and in need of cleaning, as well as how long the hardware lasts for before being considered in need of replacement (either for permanent damage such as discoloring, or general wear and tear). These two aspects are considered as the long-term lasting of the hardware itself, which is determined based on the material used in the hardware, as well as the design/shape of the device.

Friendliness “cool” factor to a stranger

Lastly, an important aspect of inclusive design is that the device isn't stigmatizing. The team recognizes the importance of the device not be associated only with locked-in syndrome disorder or any other specific disabilities. Because if you are someone with locked-in syndrome, it would be stigmatizing for you to wear a device for locked-in syndrome disorder; and it would further keep prevent someone who doesn't have the disorder and would buy/use the device from doing so. What became a more important requirement is that the hardware design of the device is inviting and useful for any person (with disability or not) to improve their quality of life, thus removing the stigma – and allowing its user to blend in. This was inspired by the design of a kitchen product for patients of arthritis (Appendix A).

Step 2: what are successful and examples of the four criteria we defined (fit comfort, ease of maintenance, friendliness "cool" factor, cleanliness for long wear)
create mood board and assessments of what we define as successful examples/products

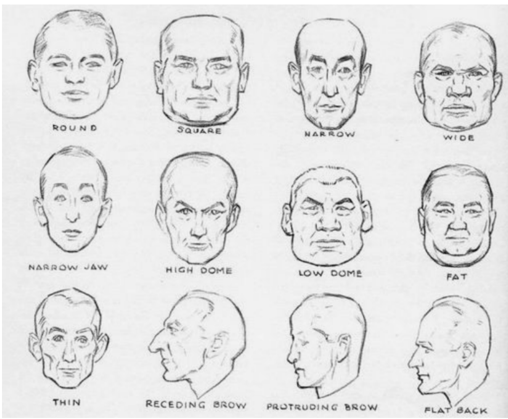
Metric (Score out of 5) /Product	Long term fit comfort	Ease of maintenance for caregiver	Friendliness "cool" factor to a stranger	Long wear cleanliness	Overall Score	Comments
Sports headwear / helmets	3	4	4	2	13	Most people think sports is relatable and cool! It's the most likely to be worn everyday, without sticking out or any connotation in public.
Religious headwear	5	4	3	3	15	Usually designed to be worn all day, and made out of cloths or more comfortable/lighter material. People think religious headwear (or any symbols) are either very relatable, or very alienating! It's the most likely to be worn everyday, either without sticking out or any connotation in public; or you would stick out in public.
Bone conducting headphones	4	5	4	5	18	Head positioning matters, as head movements may result in the headphones moving, and just affecting comfort. Easiest to clean, doesn't require going inside a volume to clear, and is not made of cloths so easy to clean. Would probably be the cleanest because they don't cover your

						entire head, so won't get as dirty
Over ear headphones (covers top of head)	3	5	4	4	16	Can give you a headache if it's too tight or the material is not designed for comfort Easier to clean, somewhat requires going inside a volume to clear, and is not made of cloths so easy to clean.
Early flying / astronauts head wear	3 for pilots cap 2 for astronauts cap	3	2	2	9 or 10	Might be the most alienating, or at the very least the wear-er would be sticking out in public.
Study/Research Helmet	3	4	2	3	12	More likely to be very alienating, or at the very least the wear-er would be sticking out in public as it can also leave the public at un-ease (given any electronics, or the unfinished nature of the products).
Regular Hats	5	4	5	3	17	Usually designed to be worn all day, and made out of cloths or more comfortable/lighter material.
Headband or headdress/jewelry	2	5 for head band 4 for headress	5	5	16 or 17	Can give you a headache if it's too tight Easiest to clean, doesn't require going inside a volume to clear, and is not made of cloths so easy to clean. Would probably be the cleanest because they don't cover your entire head, so won't get as dirty
Costume headdress	2	2	3	1	8	Might be the most alienating, or at the very least the wear-er would be sticking out in public (but most likely to be a positive sticking out in public, especially with good designs).

Figure: A comparison rating of different products considered for headwear, based on the defined metrics important for the re-design.

Figure: A mood board and a visual review of different headwear products, especially ones that are consumer friendly.

Step 3: illustrating and brainstorming different ideas of “product” solution



Figures: The difference in human face shapes, head types, ethnicities [20][21][22][23]

Product requirements, based on user research, product reviews (Appendix B), and scientific research of electrode placements and number.

- Size/circumference needs to be flexible or adjustable.
- Tightness needs to be adjustable or flexible.
- Needs to be non-alienating or does not stick out; or needs to stick out with a good/customizable design.
- Should have minimal volume to be very easy to clean.
- Stays in place.
- Should have the comfort of cloth headwear, but the ease of maintenance / to clean of metal/hard material.

- Might be great not to cover the entirety of the head, so it doesn't get as dirty over long times OR good air flow / breathable.
- Sensor placements around the head
- Electrodes should be comfy.

Further questions about design requirements, to base design on [20][21][22][23]:

- What are the different types of human head types/shapes?
- Ethnicity: Asian, African, European?
- General face shape: triangle, oval, square, etc?
- Face profile/type (from anatomy illustrations)?
- Is there a difference between a male head and a female head?

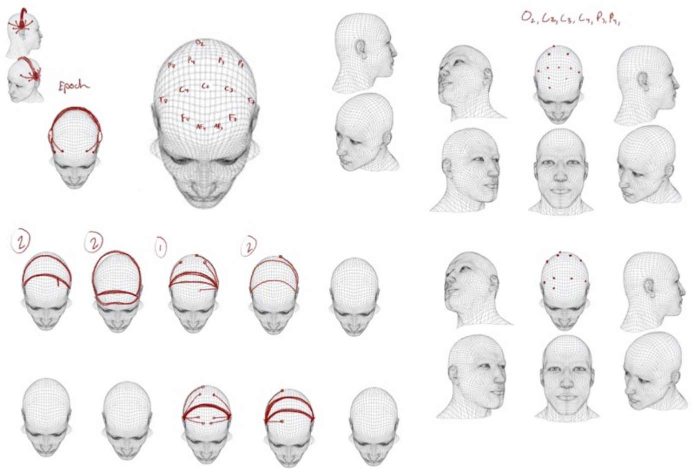


Figure: A visual review of how the electrodes fit on a head, especially comparing a current headset (EPOC) to the placements the team decided should be

Step 5: user testing and interviewing. (If enough time) iterating on prototype. (If not enough time) next iteration steps and future path. ADDED: Recording a video of prototypes or illustrations, explaining the difference (like a user testing of a software UX)

The following questions would be a determine of the success of the proposed product design, especially in comparison to the current designs of headsets.

- How long does a person keep their headset on, before feeling uncomfortable (higher is better, measured in hours or days)?
- How long does it take for a caregiver to take off, clean, and put back on the headset (lower is better, measured in minutes)?
- How friendly does a person perceive the headset (could be measured by how many "heads-turn" the headset?

Work Cited

1 - E. Smith and M. Delargy, “Locked-in syndrome,” *BMJ*, vol. 330, no. 7488, pp. 406–409, 2005.

2 - J. R. Wolpaw, H. Ramoser, D. J. McFarland, and G. Pfurtscheller, “EEG-based communication: Improved accuracy by response verification,” *IEEE Transactions on Rehabilitation Engineering*, vol. 6, no. 3, pp. 326–333, 1998.

3 - J. R. Wolpaw, N. Birbaumer, W. J. Heetderks, D. J. McFarland, P. H. Peckham, G. Schalk, E. Donchin, L. A. Quatrano, C. J. Robinson, and T. M. Vaughan, “Brain-Computer Interface Technology: A review of the first international meeting,” *IEEE Transactions on Rehabilitation Engineering*, vol. 8, no. 2, pp. 164–173, 2000.

4 - B. J. Kolls, A. H. Lai, A. A. Srinivas, and R. R. Reid, “Integration of EEG lead placement templates into traditional technologist-based staffing models reduces costs in continuous video-EEG Monitoring Service,” *Journal of Clinical Neurophysiology*, vol. 31, no. 3, pp. 187–193, 2014.

5 - K. Värbu, N. Muhammad, and Y. Muhammad, “Past, present, and future of EEG-based BCI applications,” *Sensors*, vol. 22, no. 9, p. 3331, 2022.

6 - C. Kaur and P. Singh, “EEG derived neuronal dynamics during meditation: Progress and challenges,” *Advances in Preventive Medicine*, vol. 2015, pp. 1–10, 2015.

7 - A. M. Feit, S. Williams, A. Toledo, A. Paradiso, H. Kulkarni, S. Kane, and M. R. Morris, “Toward everyday gaze input,” Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems, 2017.

8 - D. J. McFarland, A. T. Lefkowicz, and J. R. Wolpaw, “Design and operation of an EEG-based brain-computer interface with Digital Signal Processing Technology,” Behavior Research Methods, Instruments, & Computers, vol. 29, no. 3, pp. 337–345, 1997.

9 - J. Górecka and P. Makiewicz, “The dependence of electrode impedance on the number of performed EEG Examinations,” Sensors, vol. 19, no. 11, p. 2608, 2019.

10 - Neghabi M, Marateb H R, Mahnam A. Comparing Steady-State Visually Evoked Potentials Frequency Estimation Methods in Brain-Computer Interface With the Minimum Number of EEG Channels. Vol 10, Issue 3, BCN. 2019; 10 (3) :245-256, 2019

11 - F Torquato(2019). EEG data from hands movement [Data set]. Available: https://doi.org/10.34740/KAGGLE/DS/391999

12 - Google Colab. [Online]. Available: https://research.google.com/colaboratory/faq.html#resource-limits. [Accessed: 15-Jul-2022]

13 - A Gupta, “A comprehensive guide on Deep learning optimizers,” Analytics Vidhya, 24-May-2022. [Online]. Available: https://www.analyticsvidhya.com/blog/2021/10/a-comprehensive-guide-on-deep-learning-optimizers/#:~:text=The%20results%20of%20the%20Adam,for%20most%20of%20the%20applications. [Accessed: 16-Jul-2022]

14 - F. A. Moreno, "Sparse categorical cross-entropy vs categorical cross-entropy," Medium, 30-Nov-2021. [Online]. Available: https://fmorenovr.medium.com/sparse-categorical-cross-entropy-vs-categorical-cross-entropy-ea01d0392d28. [Accessed: 16-Jul-2022]

15 - F Torquato(2019). Wave brain Analysis [Notebook]. Available: https://www.kaggle.com/code/fabriciotorquato/wave-brain-analysis/log?scriptVersionId=22485756 [Accessed:09-Jun-2022]

16 - J. Kronegg, S. Voloshynovskyy, and T. Pun, *Information-transfer rate modeling of EEG-based synchronized brain-computer interfaces*, 20-Dec-2005. [Online]. Available: http://archive-ouverte.unige.ch/unige:48013.

17 - B. Dal Seno, M. Matteucci, and L. T. Mainardi, "The Utility Metric: A Novel Method to assess the overall performance of Discrete Brain–computer interfaces," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 18, no. 1, pp. 20–28, 2010.

18 - https://www.fastcompany.com/90239156/the-untold-story-of-the-vegetable-peeler-that-changed-the-world

19 - https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6751099/

20 - https://sciencing.com/types-of-human-skull-shapes-12081248.html

21 - https://boneclones.com/product/human-male-and-female-skulls-african-asian-and-european-COMP-120-SET

22 - https://www.shutterstock.com/image-vector/set-flat-face-shape-vector-people-253353472

23 - https://www.pinterest.ca/pin/574349758735229852/

24 - Relationship Between EEG Electrode and Functional Cortex in the International 10 to 20 System - PubMed (nih.gov))

25 - Sensors | Free Full-Text | Soft, Comfortable Polymer Dry Electrodes for High Quality ECG and EEG Recording (mdpi.com)

26 - Impact of the reference choice on scalp EEG connectivity estimation (uwaterloo.ca)

27 - A Comparative Study of Different EEG Reference Choices for Diagnosing Unipolar Depression - PubMed (nih.gov)

28 - (A Comparative Study of Different EEG Reference Choices for Diagnosing Unipolar Depression | SpringerLink)

29 - (Miniaturized electroencephalographic scalp electrode for optimal wearing comfort - ScienceDirect)

Appendix A – Article: The untold story of the vegetable peeler that changed the world [18]

.. she had arthritis, and she was complaining about the peeler, complaining that it was hurting her hands. … She was frustrated. The old-style metal peeler wasn't good. …

So we immediately started trying to understand the various disabilities we wanted to help. We went to the American Arthritis Foundation, and got volunteers. They introduced us to some of their staff members that had arthritis that were willing to be test subjects and talk about it.

We had to **design a handle that would work for various uses**. You might be **pulling, pushing, using it like a paintbrush** … Like the theory behind large crayons for preschoolers, they need something bigger to hang onto firmly**. It's the same thing with people with arthritis. They need something with a larger dimension.** A larger oval gave someone a little control. It was fairly short-handled because in some cases, like an apple corer, it would have to be able to fit into the palm of your hand. We also knew we **needed a special material, a tactile rubber material to get a better grip, especially when the tool was wet**.

I talked a lot about the shape, but we still **wanted some indication of where your forefinger might go on the grip**. Sam had sort of recalled seeing bicycle handle grips with thin fins on them, so we went over to a bike shop, grabbed one of these handles and brought it in, started playing with it, and that was what was the inspiration for the fins. The end result is exactly what you can see—two scooped out areas that would be under your thumb and forefinger, but they've been filled with the fins to make a simple straight handle that's all you need for a light grip. But when you want a stronger grip, your thumb and forefinger push the fins into the scooped-out areas.

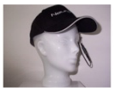
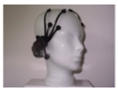
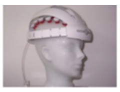
I think one of the things about this product, one of the reasons it's been so successful and lasted so many years, is that every time I tell the story of how it came about, I'll hand people the peeler, and without fail, this has probably been thousands and thousands of times–**the very first thing they do when they pick it up is start squeezing those fins with their thumb and forefinger**. Literally without fail. It's instantaneous. And as soon as they do that, they're **interacting with it in a playful way**, which says that there's something special about this handle. You could do the same thing with an ergonomic shape, maybe. You'd grab it and say, "Okay, whatever.'" **With this, the handle is almost like a conversation between your hand and the peeler itself**. They're conversing back and forth as you're pushing those fins around.

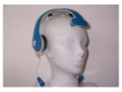
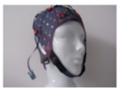
Later on, the American Arthritis Foundation gave us some recognition. We put the endorsement onto the package, but we took that off later because **we realized, one of the things that's really important for inclusive design is that the product isn't stigmatizing**. If you identify it as something for arthritis, it's stigmatizing for someone with arthritis, and it prevents someone buying it who otherwise might, because they think it's for someone with special needs. **We realized someone in need would instantly realize this was better for them, anyway.**

Meanwhile, to this day, everybody attributes the function of the peeler to the handle. But the handle isn't actually the reason why it works. The reason the peeler works so well is because the blade is really sharp. If you put a dull blade on our peeler, it won't peel any better than our peeler. .. But that was actually the secret behind it, and is true to most of the tools. The performance is more important than anything else, second to that is the design that communicated what it does.

Appendix B – Table 2 - Electroencephalography (EEG) devices used

[19] https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6751099/

EEG device	Headset	Electrode type	Number of electrodes	Weight	Description
MindCap (NeuroSky Inc, San Jose, CA, USA)		Dry	1	119 g	NeuroSky's MindCap device is a 1-channel EEG system. It comes with a frontal electrode and an ear clip reference electrode. The use of conductive gel is not necessary, and the signal is transmitted wirelessly through Bluetooth interface. The weight is 119 g. The device is recommended for neurofeedback training and gaming.
EPOC (Emotiv Inc, San Francisco, CA, USA)		Saline-based	14	116 g	Emotiv's EPOC device comes with 14 saline-based wet felt sensors. These are mounted on quite flexible plastic branches. The signal is transmitted wirelessly through Bluetooth interface. The EPOC device has a weight of 116 g.
Jellyfish (Mindo, Hsinchu, Taiwan)		Foam-based	4	95 g	Mindo's 4S Jellyfish device is a wireless dry electrode EEG device. The 4 electrodes that are mounted on a headband can be applied at either frontal or parietal sites. In our case of frontal EEG, foam-based electrodes (Figure 1, left) are recommended. In case of parietal EEG, spring-loaded pin electrodes (Figure 1, right) are to be applied. The reference is an adhesive electrode at the mastoid. The device weighs 95 g.
Trilobite (Mindo, Hsinchu, Taiwan)		3 foam-based, 29 spring-loaded pins	32	524 g	Mindo's 32 Trilobite device comprises 32 EEG channels. The frontal 3 of them are foam-based electrodes (Figure 1, left). The remaining 29 are spring-loaded pin electrodes (Figure 1, right). Furthermore, the device includes a ground and a reference electrode, both applied with a clip on the ear lobes. Signal transmission occurs wirelessly through Bluetooth. Its weight is 524 g.

BR8+ (BRI Inc, Hsinchu, Taiwan)		2 foam-based, 6 spring-loaded pins	8	269 g	BRI's BR8+ device has got 8 dry electrodes. The frontal 2 of them are foam-based electrodes (Figure 1, left). The remaining 6 are spring-loaded pin electrodes (Figure 1, right). The device includes ground and reference ear clip electrodes and a wireless signal transmission through Bluetooth. The earpads of the device do not have any technical functionality. They are thought to reduce the headset pressure and help positioning the headset at the center of the head. The BR8+ weighs 269 g.
g.SAHARA (g.tec GmbH, Graz, Austria)		Pin electrodes	16	233 g	g.tec's g.SAHARA/g.Nautilus device comprises 16 pin electrodes (Figure 2) that are mounted on a traditional EEG cap. The cap size can vary among small, medium, and large. However, to reduce financial costs, we used only the medium-sized cap. Adhesive ground and reference electrodes are applied at the mastoids. The signal is transmitted wirelessly by means of g.Nautilus device that is attached at the back of the EEG cap. It has a weight of 233 g.
g.LADYbird (g.tec GmbH, Graz, Austria)		Gel-based	16	165 g	g.tec's g.LADYbird/g.Nautilus device is a traditional gel-based EEG system with 16 active electrodes. An ear clip electrode serves as reference. Similar to the g.SAHARA/g.Nautilus device, the cap size can vary. However, in our study, we used only the medium-sized cap. The g.Nautilus device at the back of the cap allows for wireless signal transmission. The total weight of the EEG headset amounts to 165 g. Unlike the other devices, the g.LADYbird/g.Nautilus device is not designed for home and biofeedback applications. It is primarily developed for research and medical use and the treatment of locked-in patients. We included it to our study as state-of-the-art reference for EEG regarding user experience issues.