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Cognitive Control of a Hearing Aid

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COCOHA report on Alternative Technologies for Brain Signal Sensing - v1

This document provides an overview of technology alternatives to EEG for sensing brain signals. It is prepared within the context of the COCOHA project, funded by the H2020 ICT programme of the European Union under grant number 644732. COCOHA aims to help hearing impaired persons so that they can deal with challenging noisy environments, by providing them with the means to steer sophisticated acoustic processing (such as microphone arrays) with control signals derived directly from the brain. This document is available at https://cocoha.org/cocoha-reports/. See also the COCOHA report on EEG Preprocessing.

Executive summary

1. COCOHA aims to control sophisticated acoustic processing (e.g. microphone array) to isolate a target source among many for amplification by a hearing aid, on the basis of signals recorded from the brain.
2. The most common recording method is Electroencephalography (EEG) that involves placing electrodes in contact with the skin of the skull, usually with conductive gel to improve the contact.
3. Standard EEG has two drawbacks: it is obtrusive, and the signals produced are of low quality (presence of artifacts, poor signal-to-noise ratio, SNR).
4. Efforts to make improve the aesthetics and ergonomy of EEG include the use of dry electrodes and/or placement of electrodes within the ear canal or behind the ear.
5. EEG signal quality can be improved at the source (electrode quality) or by signal preprocessing, but signal quality remains poor.
6. Intrusive recording techniques (electrodes placed within the body) can provide much higher quality signals, possibly enabling a level of performance unattainable with standard EEG (electrodes on the skin). The obstacles currently seem prohibitive, but the situation might change with new technology or practices (e.g. embedding of RFID chips).
7. Alternative technologies such as ultrasound, near-infrared spectroscopy (NIRS), or magnetoencephalograpy (MEG) are currently too constraining to be suitable, but the emergence of new technologies (such as high-temperature optically-pumped MEG sensors) might suddenly change this situation. As such they are considered in this review.

1. The COCOHA context

The COCOHA project (http://cocoha.org/), funded by the EU H2020 initiative, aims at developing a "smart" hearing aid in which acoustic processing is under the control of signals from the brain. With the help of such a device, a hearing-impaired listener could focus attention on a particular sound source (for example a person speaking), and isolate it from noise and competing sources. Our intact auditory is adept at performing this task, usually without our noticing, but this ability is severely reduced by impairment. The COCOHA project aims to restore it by artificial means.

This document deals with means to record brain signals with high quality and reliability. It is worth noting that similar issues are addressed in the literature of the highly active field of Brain Computer Interfaces (BCI) (Wolpaw and Wolpaw 2012).

2. Brain signal quality

A major hurdle is that brain signals are difficult to record. Electrical activity in the brain is of very low amplitude, and by the time it reaches the skin of the skull (where it is recorded) it is severely corrupted by many sources of noise and artifact. Sophisticated signal processing algorithms exist to improve signal quality (See COCOHA Report on EEG Preprocessing), but the question of how to improve signal quality at the source remains crucial.

With ~ 90 billion neurons and an order of magnitude more synapses, the human brain is an extremely complex machine (Herculano-Houzel 2012). EEG can record signals from anywhere between a handful of electrodes to a dense array of up to 1024 electrodes, so the number of "observable" signals is much smaller than the number of brain signals to observe, and the picture obtained is necessarily impoverished. Furthermore, current spread between cortical sources and electrodes implies that each electrode picks up multiple sources, whereas each source impinges upon multiple electrodes. The resulting many-to-many mapping between sources and electrodes greatly complicates the task of isolating useful activity, because useful signals are mixed with irrelevant cortical activity on every electrode. Finally, in addition to such irrelevant cortical activity, there are numerous non-cortical sources of noise and artifact that contaminate the signals, such as power-line noise (50 or 60 Hz), electromagnetic interference (e.g. from cell phones), skin-electrode contact noise, muscular artifacts, eye-blinks, etc. The amplitude of unwanted signals can *greatly exceed* that of useful signals, in which case the data cannot be exploited without preprocessing.

Noise sources can be divided into three classes: (1) *environmental*, such as power lines or electromagnetic sources, (2) *instrumental*, such as electrode/skin contact noise or quantization noise, and (3) *physiological*, including muscle artifacts, eye-blinks, cardiac signals, and irrelevant neural activity. EEG noise sources are reviewed in further detail in COCOHA Report on EEG preprocessing.

3. Additional constraints

Additional constraints include ergonomics, aesthetics, safety, ethics, manufacturability, reliability, cost, intellectual property, regulatory constraints, and so-on. For example, a device or technology might provide good signals, but be inacceptable to the user because too complex or constraining (for example it requires applying electrode gel), or ugly, or unsafe (risk of irritation or infection), or too expensive, or hard to manufacture reliably, or covered by patents owned by a proponent of a different technology, etc. Hearing aid manufacturers are familiar with this sort of constraint. It should be kept in mind that these constraints can shift, for example with changes in technology or market (e.g. smartphones, wearables, etc.).

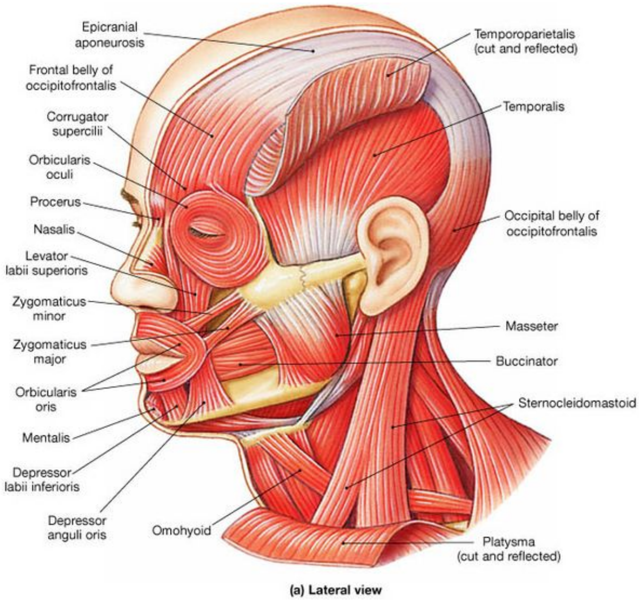
3. Main factors affecting EEG signal quality

Instrumentation. Standard laboratory EEG systems include high-impedance amplification at the electrodes ("active electrodes"), active shielding, "common-mode sense" (CMS) and "driven right leg" (DRL) feedback loop for maximal common mode rejection (see useful background information at https://www.biosemi.com/faq/cms&drl.htm and https://www.biosemi.com/faq/shielding%20vs%20active%20electrodes.htm), low noise amplification, and analog-digital conversion (ADC) with wide dynamic range (e.g. 24 bits) with sampling rates up to 10 kHz or more.

In a hearing-assistive device, cost or power constraints might require impose less good performance. Conversely, small size and isolation from power lines may reduce the sensitivity to environmental noise.

Electrode noise. Standard EEG systems use silver-silver chloride electrodes together with chloride gel to improve the skin-electrode interface. Compared to alternatives (gold, platinum, stainless steel) this provides best electrode stability (Albulbul 2016, Hokajärvi 2012, Huigen et al 2012) and smallest amount of electrode drift, which is important to provide access to information in the low-frequency region of the EEG (Vanhatalo et al 2005) that we have found useful for audio-EEG decoding in the COCOHA project (de Cheveigné et al 2017). Electrode drift can be reduced by abrading or piercing the uppermost layer of the skin, the stratum corneum (Vanhatalo et al 2005, Stjerna et al 2010) however users might be reticent towards this operation. This also reduces noise due to displacement of the electrode relative to the skin (Vanhatalo et al 2005) as when a subject moves. Electrode noise is a major concern for COCOHA.

Muscle, eye, and tongue artifacts. Subcutaneous muscle activity constitutes a major source of contamination, with signals dominated mainly (but not exclusively) by high frequencies (see de Cheveigné 2016 for a review). Muscles are present over much of the skull:



Head muscles (from https://www.pinterest.com/pin/496310821410763801/)

Myogenic activity can be suppressed by administering curare (Whitham et al 2007) but this is not readily transposable to wide-spread use. The prevalence of muscle artifacts appears to be highly subject-dependent. In the lab it is usually recommended to minimize stress and avoid intake of caffeine, but this too cannot be transposed outside the lab.

The eye is electrically charged, and ocular motion produces high-amplitude artifacts. The tongue is also electrically charge, and movements of the tongue (for example when speaking) also produce high-amplitude artifacts. These can be minimized in an experimental setting (by appropriate instructions to the subject) but not in a device used in a daily setting. Solutions may involve recording these sources independently (e.g. using an eye-tracker) and using regression or data-weighting techniques to minimize their impact.

Environmental noise. Many environments are subject to high-amplitude electric, magnetic, and electromagnetic fields due to power lines (50 or 60 Hz and harmonics), machinery and vehicles (low frequency components), electronics and displays (often in the kHz range), cellular phones and relays, television and radio transmitters, etc. Efforts made in the laboratory setting to minimize them (for example Faraday shielding) are not easily transposable to a daily environment. Conversely, a portable device may be less prone to interference because it does not involve equipment connected to a power plug, and because small size of leads, etc. may minimize coupling to electromagnetic fields. Environmental noise components can also be suppressed algorithmically.

A COCOHA-based device needs to control all these sources of noise.

4. New trends in EEG electrode and recording technology

Current thinking is dominated by lab-type EEG technology (Ag-AgCl electrodes with gel on scalp or within/circa ear) but signal quality and other concerns make alternatives worth monitoring. Technology that seems prohibitive today may tomorrow be feasable.

Portable devices. A recent advance is the development of portable and wireless devices. An advantage over standard laboratory equipment is that the subject is free to move, another is that electromagnetic interference may be reduced (no long leads, no connection to the power grid), as may be artifacts from movement relative to a tethered cable. Early wireless devices were consumer-oriented with limited data quality (noise, number of electrodes), but recent devices promise high quality data. See https://www.researchgate.net/post/What_is_are_the_best_wireless_EEG_headset_systems_for_research_high_temporal_and_spatial_resolution_How_much_does_it_cost

for some pointers. Among products on the market:

https://mbraintrain.com/smarting/
http://www.cognionics.com/index.php/products/hd-eeg-systems/mobile-eeg-cap

https://www.emotiv.com

https://www.biopac.com/product/mobita-32-channel-wireless-eeg-system/

http://www.advancedbrainmonitoring.com/neurotechnology/

http://www.gtec.at/Products/Hardware-and-Accessories/g.Nautilus-Specs-Features

http://www.neuroelectrics.com/products/enobio/

There is a steady stream of academic papers discussing wireless EEG technology and new systems (Mihajlovic 2015). Wireless communication avoids the need to tether the electrode array to a base device, but it may also allow communication between subarrays (for example between arrays at each ear) or even between electrodes (Serpedin et al 2008, Bertrand 2015). Hearing aid applications already use wireless transmission for audio (e.g. between on-ear devices and phone).

Specialized geometries. An EEG array covering the head is hard to sell, and efforts have been devoted to less obtrusive geometries. The EarEEG, CEEgrid, and similar concepts (Looney et al 2012, Bleichner et al 2015, Debener et al 2015, Bleichner et al 2017, Goverdowsky et al 2017) involve multiple electrodes within the ear canal or behind the ear. An advantage, in addition to reduced visibility and obtrusiveness, it that the path seems easy to integrate such arrays with a hearing aid. Disadvantages (especially for EarEEG) are that electrodes are close (i.e. likely to provide redundant signals) and there is no access to a distant reference electrode (adding one would reduce the appeal of the compact geometry). The EarEEG has been investigated within the COCOHA project.

Dry electrodes. A major obstacle to a "user-friendly" EEG device is the need to apply gel between electrode and skin. The use of silver-chloride gel is important for signal quality (Huigen et al 2012). There have been multiple attempts to develop "dry" electrodes that do not require gel (Dias et al 2010, Gargiulo et al 2010, Chi et al 2010, Fiedler et al 2015). Reports on signal quality are conflicting, some claiming quality similar to gel electrodes, others not.

Novel electrode technologies. An alternative route to unobtrusiveness is to use miniaturized electrodes (Nikulin et al 2010). There is large body of recent work on flexible, elastic, or printable electrodes (e.g. Norton et al 2015, Myllymaa et al 2015, Sekitani et al 2016).

5. Invasive recording

The skin-electrode interface is a major barrier to obtaining the high-quality signals required by a COCOHA-style application. This motivates working on invasive alternatives, despite the obvious concerns associated with breaking the skin barrier. The obstacle may be less forbidding than it seems: piercings and body art are commonplace, despite obvious risks, and implantation of RFID chips is becoming standard (https://en.wikipedia.org/wiki/Microchip_implant_(human)). The benefit of a cochlear implant is thought to overweigh cost and risk, and a similar argument might be made for a brain recording implant if sufficient benefit for a hearing-impaired subject can be demonstrated.

At least one implantable system is in clinical tests (http://hyposafe.com), based on subcutaneous electrodes that receive power and transmit information by an inductive loop (Duun-Henriksen et al 2015). More ambitious ideas have been put forward, such as "syringe-injectable electronics" (Liu et al 2015), or "neural dust" (Seo et al 2016). Neural dust consists of tiny "motes" that are powered and addressed by ultrasonic signals from outside the head (Bertrand et al 2014). Deeper electrodes (e.g. within the central nervous system) raise the stakes by providing better signal quality at greater potential risk. Experiments with electrodes implanted in epileptic patients indeed show that signals can be decoded with much better performance than those collected non-invasively (e.g. Mesgarani and Chang 2012).

6. MEG and ultrasound

The earliest proposal for cognitive control of a hearing aid (Higuchi et al 2009) involved Magnetoencephalography (MEG), and many studies supporting the idea have been conducted using MEG (e.g. Ding and Simon 2012). MEG offers generally better signal quality than EEG, leading to better decoding performance (e.g. Koskinen and Seppä 2014). Up to now, MEG required SQUID sensors cooled with liquid helium, and placing both the system and the subject within a heavily-shielded room (with layers of Mu-metal and aluminium). The first requirement (liquid helium) seems about to be lifted with the development of sensitive, low-noise optically-pumped sensors (Boto et al 2017). The latter (shielding) may conceivably be addressed by smart active shielding methods.

7. Enabling computational technologies

The development of new sensor technologies (or improvement of existing technologies) may hinge in part on the development of new algorithms and computing technologies, in particular to harness *large numbers of sensors* (such as might become available with miniaturized sensor arrays), to *fuse multiple sources of information* (in particular to factor out noise), and for *active sensor control* (for example to improve dynamic range). Some work in this direction has been carried out within the COCOHA project (e.g de Cheveigné 2016).

Summary

Electrical signals recorded by standard EEG electrodes are extremely noisy, and this is a major obstacle for deriving robust control signals for applications such as explored in the COCOHA project. This motivates consideration of other technologies. Some may seem far-fetched or unrealistic at this point, but shifts in technology, regulation, market forces, etc. can radically change the landscape in the future. It is good to keep these ideas on our radar screen.

References

Albulbul, A. (2016). Evaluating Major Electrode Types for Idle Biological Signal Measurements for Modern Medical Technology. Bioengineering, 3(3), 20. https://doi.org/10.3390/bioengineering3030020

Bashashati, A., Fatourechi, M., Ward, R. K., & Birch, G. E. (2007). A survey of signal processing algorithms in brain–computer interfaces based on electrical brain signals. Journal of Neural Engineering, 4(2), R32–R57. Retrieved from http://stacks.iop.org/1741-2552/4/i=2/a=R03?key=crossref.cdbb14e4d6a8a03f7c5a86bc262cb3a9

Bertrand, A., Seo, D., Maksimovic, F., Carmena, J. M., Maharbiz, M. M., Alon, E., & Rabaey, J. M. (2014). Beamforming approaches for untethered, ultrasonic neural dust motes for cortical recording: a simulation study. Conference Proceedings : ... Annual International Conference of the IEEE Engineering in Medicine and Biology Society. IEEE Engineering in Medicine and Biology Society. Annual Conference, 2014, 2625–2628. https://doi.org/10.1109/EMBC.2014.6944161

Bleichner, M. G., Lundbeck, M., Selisky, M., Minow, F., Jager, M., Emkes, R., ... De Vos, M. (2015). Exploring miniaturized EEG electrodes for brain-computer interfaces. An EEG you do not see? Physiological Reports, 3(4), e12362–e12362. https://doi.org/10.14814/phy2.12362

Bleichner, M. G., & Debener, S. (2017). Concealed, Unobtrusive Ear-Centered EEG Acquisition: cEEGrids for Transparent EEG. Frontiers in Human Neuroscience, 11(April), 1–14. https://doi.org/10.3389/fnhum.2017.00163

Boto, E., Meyer, S. S., Shah, V., Alem, O., Knappe, S., Kruger, P., ... Brookes, M. J. (2017). A new generation of magnetoencephalography: Room temperature measurements using optically-pumped magnetometers. NeuroImage, 149, 404–414. https://doi.org/10.1016/j.neuroimage.2017.01.034

Chi, Y. M., Jung, T. P., & Cauwenberghs, G. (2010). Dry-contact and noncontact biopotential electrodes: Methodological review. IEEE Reviews in Biomedical Engineering, 3, 106–119. https://doi.org/10.1109/RBME.2010.2084078

de Cheveigné, A., & Simon, J. Z. (2008). Denoising based on spatial filtering. Journal of Neuroscience Methods, 171(2), 331–339. Retrieved from http://linkinghub.elsevier.com/retrieve/pii/S0165027008002008

de Cheveigné, A., & Simon, J. Z. (2008). Sensor noise suppression. Journal of Neuroscience Methods, 168(1), 195–202. Retrieved from http://linkinghub.elsevier.com/retrieve/pii/S0165027007004621

de Cheveigné, A. (2010). Time-shift denoising source separation. Journal of Neuroscience Methods, 189(1), 113–120. Retrieved from http://linkinghub.elsevier.com/retrieve/pii/S0165027010001202

de Cheveigné, A. (2012). Quadratic component analysis. NeuroImage, 59(4), 3838–3844. Retrieved from http://linkinghub.elsevier.com/retrieve/pii/S1053811911012560

de Cheveigné, A., & Parra, L. C. (2014). Joint decorrelation, a versatile tool for multichannel data analysis. NeuroImage, 98, 487–505. Retrieved from http://linkinghub.elsevier.com/retrieve/pii/S1053811914004534

de Cheveigné, A., & Arzounian, D. (2015). Scanning for oscillations. Journal of Neural Engineering, 12(6), 66020. Retrieved from http://adsabs.harvard.edu/cgi-bin/nph-data_query?bibcode=2015JNEng..12f6020D&link_type=EJOURNAL

de Cheveigné, A., Wong, D., Hjortkjaer, J, Slaney, M, Lalor E (submitted to NeuroImage) Decoding the auditory brain with Canonical Correlation Analysis.

de Cheveigné, A. (2016). Sparse time artifact removal. Journal of Neuroscience Methods, 262, 14–20. Retrieved from http://dx.doi.org/10.1016/j.jneumeth.2016.01.005

Debener, S., Emkes, R., De Vos, M., & Bleichner, M. (2015). Unobtrusive ambulatory EEG using a smartphone and flexible printed electrodes around the ear. Scientific Reports, 5(1), 16743. https://doi.org/10.1038/srep16743

Dias, N. S., Carmo, J. P., Da Silva, A. F., Mendes, P. M., & Correia, J. H. (2010). New dry electrodes based on iridium oxide (IrO) for non-invasive biopotential recordings and stimulation. Sensors and Actuators, A: Physical, 164(1–2), 28–34. https://doi.org/10.1016/j.sna.2010.09.016

Ding N, Simon JZ (2012) Neural coding of continuous speech in auditory cortex during monaural and dichotic listening. Journal of Neurophysiology 107:78–89.

Duun-Henriksen, J., Kjaer, T. W., Looney, D., Atkins, M. D., Sørensen, J. A., Rose, M., … Juhl, C. B. (2015). EEG Signal Quality of a Subcutaneous Recording System Compared to Standard Surface Electrodes. Journal of Sensors, 2015, 1–9. https://doi.org/10.1155/2015/341208

Fatourechi M, Bashashati A, Ward RK, Birch GE (2007) EMG and EOG arti-facts in brain computer interface systems: A survey. Clinical Neurophysiol- ogy 118:480–494.

Fiedler, P., Pedrosa, P., Griebel, S., Fonseca, C., Vaz, F., Supriyanto, E., … Haueisen, J. (2015). Novel Multipin Electrode Cap System for Dry Electroencephalography. Brain Topography, 28(5), 647–656. https://doi.org/10.1007/s10548-015-0435-5

Gargiulo, G., Calvo, R. A., Bifulco, P., Cesarelli, M., Jin, C., Mohamed, A., & van Schaik, A. (2010). A new EEG recording system for passive dry electrodes. Clinical Neurophysiology, 121(5), 686–693. https://doi.org/10.1016/j.clinph.2009.12.025

Goncharova II, McFarland DJ, Vaughan TM, Wolpaw JR (2003) EMG contamination of EEG: spectral and topographical characteristics. Clinical Neurophys- iology 114:1580–1593.

Goverdovsky, V., von Rosenberg, W., Nakamura, T., Looney, D., Sharp, D. J., Papavassiliou, C., … Mandic, D. P. (2017). Hearables: Multimodal physiological in-ear sensing. Scientific Reports, 7(1), 6948. https://doi.org/10.1038/s41598-017-06925-2

Grosse-Wentrup, M., Liefhold, C., Gramann, K., & Buss, M. (2009). Beamforming in noninvasive brain-computer interfaces. Biomedical Engineering, IEEE Transactions on, 56(4), 1209–1219.

Higuchi, M (2009) A method for the identification of listened sound from MEG data. The Journal of Japan Biomagnetism and Bioelectromagnetics Society, 1, 82-83 (in Japanese).
Hokajärvi I.A. Master's Thesis. Tampere University of Technology; Tampere, Finland: 2012. Electrode Contact Impedance and Biopotential Signal Quality.
Huigen, E.; Peper, A.; Grimbergen, C.A. Investigation into the origin of the noise of surface electrodes. Med. Biol. Eng. Comput. 2002, 40, 332–338.
Koskinen M, Seppä M (2014) Uncovering cortical MEG responses to listened audiobook stories. NeuroImage 100:263–270.
Liu, J., Fu, T.-M., Cheng, Z., Hong, G., Zhou, T., Jin, L., … Lieber, C. M. (2015). Syringe-injectable electronics. Nature Nanotechnology, 10(7), 629–636. https://doi.org/10.1038/nnano.2015.115
Looney, D., Kidmose, P., Park, C., Ungstrup, M., Rank, M., Rosenkranz, K., & Mandic, D. (2012). The in-the-ear recording concept: user-centered and wearable brain monitoring. IEEE Pulse, 3(6), 32–42. Retrieved from http://eutils.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?dbfrom=pubmed&id=23247157&retmode=ref&cmd=prlinks
Ma J, Tao P, Bayram S, Svetnik V (2012) Muscle artifacts in multichannel EEG: characteristics and reduction. Clinical Neurophysiology 123:1676–1686.
Mesgarani N, Chang EF (2012) Selective cortical representation of attended speaker in multi-talker speech perception. Nature 485:233–6.
Mihajlovic, V., Grundlehner, B., Vullers, R., & Penders, J. (2015). Wearable, wireless EEG solutions in daily life applications: What are we missing? IEEE Journal of Biomedical and Health Informatics, 19(1), 6–21. https://doi.org/10.1109/JBHI.2014.2328317
Myllymaa, S., Lepola, P., Töyräs, J., Hukkanen, T., Mervaala, E., Lappalainen, R., & Myllymaa, K. (2013). New disposable forehead electrode set with excellent signal quality and imaging compatibility. Journal of Neuroscience Methods, 215(1), 103–109. https://doi.org/10.1016/j.jneumeth.2013.02.003
Nikulin, V. V., Kegeles, J., & Curio, G. (2010). Miniaturized electroencephalographic scalp electrode for optimal wearing comfort. Clinical Neurophysiology, 121(7), 1007–1014. https://doi.org/10.1016/j.clinph.2010.02.008
Norton, J. J. S., Lee, D. S., Lee, J. W., Lee, W., Kwon, O., Won, P., … Rogers, J. A. (2015). Soft, curved electrode systems capable of integration on the auricle as a persistent brain–computer interface. Proceedings of the National Academy of Sciences, 112(13), 3920–3925. https://doi.org/10.1073/pnas.1424875112
Sekitani, T., Yokota, T., Kuribara, K., Kaltenbrunner, M., Fukushima, T., Inoue, Y., … Someya, T. (2016). Ultraflexible organic amplifier with biocompatible gel electrodes. Nature Communications, 7, 11425. https://doi.org/10.1038/ncomms11425
Seo, D., Neely, R. M., Shen, K., Singhal, U., Alon, E., Rabaey, J. M., … Maharbiz, M. M. (2016). Wireless Recording in the Peripheral Nervous System with Ultrasonic Neural Dust. Neuron, 91(3), 529–539. https://doi.org/10.1016/j.neuron.2016.06.034
Serpedin, E., Li, H., Dogandžić, A., Dai, H., & Cotae, P. (2008). Distributed signal processing techniques for wireless sensor networks. EURASIP J. Adv. Signal Process., 23(6), 923–935. https://doi.org/10.1155/2008/540176
Stjerna S, Alatalo P, Mäki J, Vanhatalo S (2010) Evaluation of an easy, standardized and clinically practical method (SurePrep) for the preparation of electrode-skin contact in neurophysiological recordings. Physiological measurement 31:889–901.
Vanhatalo, S., Voipio, J., & Kaila, K. (2005). Full-band EEG (FbEEG): An emerging standard in electroencephalography. Clinical Neurophysiology, 116(1), 1–8. https://doi.org/10.1016/j.clinph.2004.09.015
Whitham EM, Pope KJ, Fitzgibbon SP, Lewis T, Clark CR, Loveless S, Broberg M, Wallace A, DeLosAngeles D, Lillie P, Hardy A, Fronsko R, Pulbrook A, Willoughby JO (2007) Scalp electrical recording during paralysis: quantitative evidence that EEG frequencies above 20 Hz are contaminated by EMG. Clinical Neurophysiology 118:1877–1888.

J. Wolpaw and E. Wolpaw, Brain-computer interfaces: principles and practice. Oxford University Press, 2012