Electroencephalography (EEG)

GLENNA L. READ and ISAIAH J. INNIS
Indiana University, USA

Although keeping us alive is arguably the most important function of the human brain, the brain is responsible for a host of functions—including processing of environmental stimuli. Electroencephalography (EEG) is a noninvasive technique that provides a direct measure of brain electrical activity through placement of electrodes on the scalp. EEG measures electrical activity instantaneously with high precision. Through the analysis of event-related brain potentials (ERPs) and frequencies, EEG allows researchers to investigate psychological mechanisms underlying perception and behavior. EEG provides high-resolution real-time data that is able to capture rapid, implicit processes not revealed through self-report.

History

In 1929 Hans Berger demonstrated the electrical activity of the human brain through a series of experiments. By placing electrodes on the scalp and amplifying the signal, Berger determined that changes in voltage resulting from electrical activity in the brain could be plotted and measured—thus inventing (and recording) the first electroencephalogram (EEG). Berger posited that oscillations in the EEG might be related to cognitive activity in humans. Although neurophysicists were skeptical at first, other researchers subsequently confirmed this observation (Adrian & Matthews, 1934). In 1964, Walter and colleagues reported the first ERP component, known as the contingent negative variation (CNV) (Walter, Cooper, Aldridge, McCallum, & Winter, 1964). This ERP reflected cognitive preparation for a future stimulus and its discovery prompted further investigation into ERP components. In 1965 researchers discovered the P3 component (Sutton, Braren, Zubin, & John, 1965), one of the most studied components to date. In the late 1960s and 1970s researchers were most interested in discovering new ERP components rather than addressing questions of broad scientific importance. As a result, ERP research decreased in reputation. However, in the late 1980s increased application of ERP research to broad questions of general scientific interest heightened interest and enthusiasm in the technique (Luck, 2014).

The International Encyclopedia of Communication Research Methods. Jörg Matthes (General Editor), Christine S. Davis and Robert F. Potter (Associate Editors).

DOI: 10.1002/9781118901731.iecrm0080

Physiological mechanism

EEG measures fluctuations in electrical activity of the brain over time. This electrical activity usually ranges from −100 to +100 μV. Recordings appear as positive and negative deflections that can be analyzed for frequency, amplitude, and latency, all of which may have psychological meaning. The brain electrical activity measured by EEG originates from summed postsynaptic potentials of cortical neurons. Postsynaptic potentials are the voltages that arise after an action potential when neurotransmitters are released and bind to a postsynaptic cell, altering the passage of ions across a cell membrane. Postsynaptic potentials can be the result of localized depolarization (excitatory postsynaptic potentials) or hyperpolarization (inhibitory postsynaptic potentials) caused by the action potential. Postsynaptic potentials in similarly stimulated cells tend to be synchronous and last for tens to hundreds of milliseconds. The EEG recording reflects the summation of postsynaptic potentials of groups of cortical neurons arranged perpendicular to the scalp. The postsynaptic potential creates an electrical dipole. Cortical neurons are organized in a columnar structure in which the orientation of their electrical fields are aligned. This enables the signal from multiple neurons to be summated. EEG is only able to pick up activity at the end of electrical dipoles of the synchronously firing neurons that are oriented perpendicular to the scalp. EEG does not pick up the contrapolar dipole. Some cortical neurons are not organized in this columnar fashion (e.g., those in the amygdala) and are therefore unable to be detected using EEG. Dipoles of opposing polarity that are oriented toward each other cancel out, so that neither dipole is detected.

Event-related potentials

An event-related potential (ERP) is an index of brain activity revealed through systematic changes in electrical activity generated by primarily cortical neurons. As the name implies, ERPs are electrical potentials that are associated with specific events. ERPs are indicative of a number of cognitive activities that are associated with the presence of a stimulus or response. For example, ERPs that occur relatively early after a visual stimulus may fluctuate based on certain physical aspects of the stimulus. ERPs are useful for measuring rapid and implicit cognitive activity because they allow researchers to examine brain wave fluctuations instantaneously and with high temporal precision. Thus, researchers may investigate ERPs that occur before conscious awareness of a stimulus and track how response changes over time. Further, as ERPs are rapid and automatic, they are less susceptible to concerns of social desirability than some behavioral measures.

An EEG waveform has positive and negative voltage deflections that may be referred to as waves or peaks. If a waveform is reliably elicited by a particular stimulus, is associated with a specific cognitive process, and has a circumscribed scalp distribution, then it is referred to as an ERP component. ERP components are often named based on the direction of the deflection and the latency in milliseconds. The letter "P" precedes positive components. The letter "N" precedes negative components. For example,

a positive deflecting component that occurs around 300 milliseconds after stimulus onset is named P300. Similarly, a negative deflecting component that occurs around 100 milliseconds after stimulus onset is named N100. Often, the timing of the ERP components is relative, not precise, and may be influenced by a variety of experimental factors. This means that the third positive deflection may be labeled P300 even if it occurs after 400 milliseconds. For this reason, some researchers prefer to refer to components based on their ordinal position. Thus, sometimes the names of ERPs are shortened such that P300 becomes P3. This entry will refer to ERPs by their ordinal position. Historically, components were plotted with negative deflections up. However, contemporary researchers tend to plot components with positive deflections up. When reading ERP literature it is important to check the axes of a scale to determine how the researcher has plotted the components.

The amplitudes of ERP components are much smaller than raw EEG in general. Thus, in order to be seen, these waveforms must be averaged over many trials—from 10 up to 500 trials depending on the ERP component to be analyzed. By using event codes to indicate when an event occurs researchers may align the EEG and average waveforms over many trials. Brain activity unrelated to the event fluctuates from positive to negative and is inconsistent in regards to the timing of the event. Through averaging, the unrelated signal will approximate zero. In contrast, ERP components occur consistently in a time-locked manner and are not eliminated by averaging the signal; thus, averaging results in the elimination of unrelated EEG waves while retaining ERPs.

ERP components can be analyzed for amplitude or latency. Amplitude of an ERP component is thought to indicate the extent to which operations are engaged. Greater magnitude components, both positive and negative in direction, may reflect a larger cognitive response. Latency is thought to reflect the time at which operations have been completed. Increased latency indicates that operations were completed at a later time. Inferential statistics may be used to analyze peak amplitude, mean amplitude, or latencies.

Stimulus-locked ERP responses are positive and negative deflections in the waveform that are time- and phase-locked to specific stimuli. Endogenous ERPs are those that are influenced by subjects' perceptions or interpretations of stimuli. In contrast, exogenous ERPs are those that correspond with the physical nature of the stimulus. According to Bartholow and Amodio (2009), the functional significance of the ERP depends on several things including the stimulus, nature of the task, the timing, location on the scalp, and the researcher's theoretical perspective. Additionally, interpretation of the ERP may differ based on the modality of the stimulus. For example, the same ERP can indicate different processes when elicited by a visual, versus auditory, stimulus. The following descriptions are intended as a brief overview of some ERP components.

Early ERPs are thought to indicate automatic processing. Two early ERPs potentially of interest to media researchers are the P1 and the N1. These two components reflect attentional processes such that greater amplitude is indicative of more attention to a stimulus. The P1 is affected by selective attention processes, arousal, and visual parameters of a stimulus. The N1 follows the P1 and is modulated by spatial attention and discriminative processing. The N1 has also been associated with the processing of and attention toward auditory stimuli. A negative deflecting ERP that may follow is the

N170. The N170 is a component that fluctuates in response to the presence or absence of faces and is indicative of facial processing. The N170 is also enhanced for experts when viewing the subject of their expertise (e.g., bird experts viewing birds; Tanaka & Curran, 2001).

Later ERPs often reflect controlled cognitive processing. The P3 is an oft-studied component that occurs 300–800 ms after stimulus onset. The P3 is associated with the processing of novelty. The P3 is often examined in response to a task known as the "oddball paradigm" in which repetitive stimuli are presented and then interrupted by a deviant stimulus. Amplitude of the P3 increases as the perceived probability of an event decreases. In an oddball task, the amplitude of the P3 is enhanced in response to the deviant stimulus compared to the repetitive stimulus. The P3 is also thought to index "context updating" of the state of the environment (Donchin, 1981). Greater latency of the P3 reflects more effortful categorization of a stimulus. The negative slow wave (NSW) is a sustained negative deflection seen during the maintenance period of working memory tasks. Amplitude of the NSW increases as memory load in these tasks increases. The NSW also indexes cognitive processes associated with self-regulation and the ability of a participant to overcome cognitive conflict.

Some ERPs are also affected by perceived emotional content of stimuli. For example, amplitudes of P1, N1, N170, and P3 components are enhanced for emotional stimuli compared to neutral stimuli. Two components of interest are the early posterior negativity and the late positive potential. The early posterior negativity is enhanced for emotion-evoking stimuli of positive valence. The late positive potential is thought to reflect "intrinsic task relevance of emotion-related stimuli" (Luck, 2014, p. 107).

Other ERPs are time-locked to a behavioral response and thus may fluctuate based on the formation and regulation of the response. Two components in particular—the error-related negativity (ERN or N_e) and the error-related positivity (P_e) may be of interest to media researchers. The ERN is a negative deflection that tends to occur 50–80 ms after an erroneous behavioral response. The ERN is associated with conflict monitoring in the dorsal anterior cingulate cortex (dACC). The presence of the ERN does not require that one is consciously aware that an error has been made, although conscious awareness of the error does enhance the amplitude of the ERN. The P_e is a positive deflection sometimes seen after the ERN. The peak amplitude of this component occurs 250–400 ms after one has made an incorrect response. In contrast to the ERN, the P_e occurs when one is consciously aware of having made an error. The P_e is associated with the cognitive process of monitoring for conflict between the preceding behavior and certain external cues regarding regulation of the response.

Some ERPs occur as a participant prepares for an upcoming stimulus or response. These anticipatory components are thought to reflect attention and control. They can also be used to investigate the extent to which a participant is motivated to engage with the stimulus. Some examples of anticipatory components are the contingent negative variation (CNV) and the readiness potential. The CNV is an ERP with a negative deflection that is used as an expectancy measure. For example, the CNV is enhanced if there is an expectation that another stimulus will follow. Some ERPs precede and accompany movement—these ERPs are known as readiness potentials. The lateralized readiness

potential (LRP) is a slow negative ERP that occurs before a motor movement is initiated and reflects preparation for an upcoming motor response. The LRP is most pronounced over the motor cortex (located in the rear of the frontal lobe of the brain) contralateral to the moving hand.

Frequency bands

As is apparent from visual inspection, EEG is a complex signal composed of multiple frequencies oscillating simultaneously. In the brain, lower frequencies show greater power than higher frequencies, with power decreasing as the frequency increases. The majority of brain activity occurs at frequencies under 100 Hz. The frequency spectrum of the brain is divided into different bands of activity based around a center frequency. These bands and their ranges are, in increasing frequency order: delta (<4 Hz), theta (4–7 Hz), alpha (8–13 Hz), beta (14–30 Hz), and gamma (>35 Hz). Alpha activity has more power than beta activity, which has more power than gamma activity. Of these, alpha is perhaps the easiest to see, appearing as large rhythmic waves visible to the naked eye in an EEG signal. It should be noted that while the center frequency of each band never changes (e.g., alpha always straddles 10 Hz), the boundaries of the bands are imprecise. For example, some may report alpha as 8–13 Hz or beta as 15–30 Hz.

These EEG frequency bands are associated with psychological phenomena. Delta is often associated with drowsiness, sleep, and states of altered consciousness. Theta appears to serve as a carrier wave for and modulator of the other oscillations and is associated with the cessation of pleasurable activity. Alpha activity is associated with attention and inhibitory control in the brain. Alpha activity is most prominent during relaxation and is inversely related to brain activity, as indicated by PET and fMRI studies (Cook, O'Hara, Uijtdehaage, Mandelkern, & Leuchter, 1998; Goldman, Stern, Engel, & Cohen, 2002). Interruption of alpha, known as alpha blocking, occurs during cognitive tasks. During alpha blocking, alpha waves are replaced with higher frequency, lower amplitude beta waves. Beta activity occurs when one is alert and is related to the regulation of processing states. Finally, gamma activity is associated with object maintenance, memory, and a variety of cognitive processes.

The EEG signal is collected in the time domain and must be converted to the frequency domain before these bands can be analyzed. This is done using the Fourier transform. Fourier posited that a time series may be represented by the sum of series of sine waves and a coefficient corresponding to how much of that sine wave is needed to reconstruct the original signal. In reverse, multiplying these sine waves by their associated coefficient and adding them together will reproduce the starting waveform. These principles form the basis of frequency analysis. In EEG research, a Fourier transform is used to decompose the EEG into a series of frequency coefficients that represent the amount of power at each frequency needed to reconstruct the original waveform. Practically, this labels the amount of power at each frequency and therefore allows examination of EEG frequency bands. Stern, Ray, and Quigley (2001) describe the Fourier transform as comparing a "template" of frequencies (the sine waves) to an existing EEG signal to see how closely it matches the template. A power spectrum allows researchers

to visually represent all the frequencies present in the dataset, collapsed over time. More complex versions of this analysis are used to examine time-locked frequency variations in the waveform.

A related procedure is a coherence analysis, which provides information about how the signal from two given electrodes co-vary at a certain frequency. In other words, a coherence analysis describes how an EEG signal at "each of two electrodes is related to each electrode" (Stern et al., 2001, p. 91). A coherence analysis allows researchers to investigate the extent to which frequencies at different electrode sites are synchronous.

Recording EEG

This section provides an overview of some of the considerations for a researcher who is interested in recording EEG data. The first part of this section discusses choosing an EEG system and recording and analysis software, setting up an EEG lab, and a standard study procedure. The second part of this section describes other practical considerations including amplification, sampling rate, filtering, impedance, and referencing.

Choosing an EEG system

The biggest decision facing a researcher choosing an EEG system is the number of electrodes to use. While it is possible to record from only a few electrodes, EEG systems typically come in 32, 64, 128, or 256 channel configurations. However, some communication scholars have even used 14-channel systems (Minas, Potter, Dennis, Bartelt, & Bae, 2014). Larger systems have become more common over time. A greater number of sensors provide greater spatial resolution. However, this is at the cost of additional preparation time for the net and large file sizes for the data. Although analysis options may be limited with fewer sensors, a smaller configuration may in some cases produce higher data quality due to the ease of monitoring data during recording. Systems with fewer sensors (e.g., 14–32) also cost less than higher density systems. Therefore, dense array EEG systems with 128 channels or more may not be worth the tradeoff for some researchers. Most systems include a reference and a noise-reducing ground electrode alongside active sites. The number of electrodes needed depends on specific research questions to be addressed, but a good recommendation is to use a 64-channel system. Advanced techniques, such as source localization, require a minimum of 64 sensors. Choosing at least a 64-channel system allows a wide range of analyses to be performed.

Electrodes are usually 4–8 mm in diameter and are typically mounted in either a stretch lycra cap or an elastomer net. Silver/silver chloride (Ag/AgCl) is the preferred material for electrodes as it is nonpolarizing, stable, and has a relatively low noise level. Tin (Sn) may also be used because, like Ag/AgCl, it is highly conductive and resistant to polarization. Depending on the system, electrode caps should be replaced about once a year, but this varies with frequency of use.

A common system of locating electrodes on the scalp, also referred to as a montage, is the International 10–20 system. In this montage, electrodes are placed at sites a distance of 10% and 20% away from each other based on the distance between pre-auricular

points and the distance between the nasion (the top of the nose) and inion (the bony bump of the back of the skull). Electrodes are labeled according to the region of the brain above which they are located (O for occipital, T for temporal, C for central, F for frontal, P for parietal). Numbers on the electrodes indicate laterality and distance from the midline (labeled z). Odd numbers indicate that the electrode is on the left and even numbers indicate that the electrode is on the right. Lower numbers indicate that an electrode is farther away from the midline. This system has been modified over time to account for higher density recordings, and sensor positions are often reported in this format even if they were recorded with a different montage.

EEG systems have either low-impedance amplifiers or high-impedance amplifiers. Low-impedance systems tend to record less noise than high-impedance systems but require low-impedances at every electrode. Low impedance is achieved by cleaning or abrading the scalp and will often involve greater preparation time compared to a high-impedance system. If low-impedance systems are not given low input impedances then any advantage in data quality is lost. The need to heavily abrade the skin to lower impedances may increase infection risk, a factor that should also be considered when choosing a system. High-impedance amplifiers can tolerate both low and high impedances and, thus, should be faster to prepare for. In some cases, no abrasion of the skin is necessary, greatly reducing the chance of infection. The disadvantage of high-impedance systems is that they may record more noise due to poor common mode rejection. Therefore, the decision is principally a tradeoff between setup time and noise reduction. It is worth noting that differences in quality should be minimal, provided good procedures are followed to collect clean data. However, high-impedance amplifiers are more susceptible to low-frequency noise caused by skin potentials, an artifact consisting of large, slow voltage shifts.

Another factor to consider when selecting an EEG system is the use of gel- or saline-based systems. This distinction refers to the conductive medium used to bridge the gap between electrodes and the scalp. Both options can be used to successfully record EEG but there are some differences between them. Gel-based systems may need more preparation time, requiring abrasion and exfoliation of the scalp in order to ensure good contact. They will also leave residue in subjects' hair. Saline systems should be quicker to apply, as the cap only needs to be soaked in solution before use. The speed advantage may be offset by time-consuming adjustments to re-wet sensors that dry out over the course of the experiment. Theoretically, compared to saline-based systems, gel-based systems should provide stable impedances and superior data quality over time; additionally gel-based systems should sit statically in place better than saline nets, resulting in fewer movement artifacts. However, no formal comparison exists between the two methods, meaning that the deciding factor will probably be application time or cost. For healthy adult subjects, either approach is valid. Children or other special populations may in particular benefit from the reduced setup time of a saline system.

Software

There are a variety of proprietary and open-source software packages available for EEG recording and analysis. Some programs are capable of both recording and analysis while

others might be specialized for only one function. When choosing a software package for data analysis, it is first necessary to define what sort of analyses will be performed and then select a program that has the corresponding capabilities. Some programs may be designed with a particular procedure in mind and perform it smartly but are limited when using another method. Most, if not all, programs will be capable of ERP analysis. However, other techniques such as time-frequency, connectivity, and source localization may not be supported.

In many cases a purchased EEG system will include software developed by the manufacturer. For example, EEG systems built by EGI (Electrical Geodesics, Inc.) are bundled with their Net Station software package. It is generally advisable to use manufacturer-supplied software for recording to ensure compatibility with the hardware. However, for pre-processing and data analysis it is recommended to use an open-source toolbox (two common options are EEGLAB and ERPLAB). While proprietary software may function perfectly well, it frequently lacks access to the code used for its operations. This leads to a situation where a researcher cannot precisely determine how the software is treating the data. In addition, some proprietary packages are limited in the analysis options presented to the user, constraining what types of analysis can be done. Open-source toolboxes allow the exploration and modification of code to suit the needs of the user and therefore provide greater flexibility and transparency. Several of these toolboxes run in the MATLAB environment, which may entail a nontrivial expense. Regardless of what software is chosen, a researcher should always save every step of the analysis. This helps ensure a backup in case of data loss and also allows the user to come back at a later time and make adjustments to the data processing pipeline without having to repeat every step.

Setting up a lab

There are several general requirements for setting up an EEG lab. First and most obviously, an EEG system will be required. Next, there must be a means of sending event codes from the stimulus presentation software to the EEG recording. Without any event markers it will be impossible to time-lock the data to stimulus events or even know what was onscreen at any given moment. Will the subject make responses to the stimuli? If so, take into account the latency of the response device. For example, a standard computer keyboard may not offer good timing precision. A specialized response device may be required in these cases. In either situation the response device should be comfortable for the subject and be easy to use to prevent confusion during the task.

When setting up an EEG lab there are a number of steps that can be taken to ensure the best possible data quality. First, possible sources of electrical noise should be removed. Unnecessary equipment should not be stored in the lab. The EEG amplifier should be kept physically distant from monitors, response devices, or other equipment. One of the largest potential sources of noise is actually the stimulus presentation monitor; maintaining a distance of 70 cm^{-1} m from the subject and the screen will likely ameliorate this problem. Although not often necessary, electrical shielding of the room and equipment may be worth the cost if line noise is strong and persistent. Auditory noise is also a concern, as it may distract the subject and degrade task

performance. Therefore, avoid locating the lab near any loud facilities or machinery and, if necessary, consider some type of soundproofing.

Ideally subjects will sit in a sturdy, comfortable chair made of nonconductive material. An uncomfortable subject may fidget and introduce muscle artifacts or begin to lose interest in the task. The room should be kept at a comfortable temperature. A room that is too warm will cause subjects to sweat, introducing skin potentials into the EEG. Finally, as the EEG cap should not be removed after the experiment begins, subjects should be asked to avail themselves of lavatory facilities before starting the session.

Procedure

Each EEG session should follow a well-developed procedure and be carried out by trained personnel familiar with the system. The procedure will likely consist of: consent, a brief summary of what to expect, preparing and placing the EEG cap, running the experiment, cleanup, and debriefing.

Above all else it is important to maintain a strictly professional mindset during an experimental session. This will generate trust in the experimenter and impress upon the subject the scientific nature of the procedure, hopefully prompting them to take it seriously thereby improving task performance. An air of confidence is essential as it will reassure the subject and encourage them to engage in the process. Avoid being too jovial or empathetic, as this could alter the mood of the participant; instead maintain a posture of professional detachment. To this end, if the experimenter makes minor mistakes during the session they should not be announced to the subject, but instead be quietly corrected before continuing. Naturally, any problem that presents a danger to the subject requires the termination of the experiment.

Cell phones and other electronic devices should be removed prior to starting the session as these may cause electrical interference or simply serve as distractions. During the consent process it is important to explain what EEG is to the subject, answering any questions they have about the technology. EEG may remind them of a medical procedure and therefore may be intimidating. Showing the subject what an EEG cap looks like can help soothe any apprehension. Similarly, it is important to refer to the EEG as a series of "sensors" that rest on the head instead of "electrodes," as the latter term may invoke mental images of electrical shock. This is a particularly important convention to observe when running babies or clinical populations as subjects. Explain to the subject how the capping procedure will work and try to give them an idea of what it will feel like to wear the cap.

Follow manufacturer instructions regarding preparation of the EEG net. Saline-based systems will require the soaking of the cap in a solution for a certain period of time before use. Gel-based EEG will require that the gel be applied to the cap after placement. While the net is being prepared, participants should remove any piercings or jewelry that may catch on the net and cause discomfort to the participant or damage to the equipment. It is also helpful to ask subjects to part their hair evenly down the middle to ensure a symmetric, even fit for the cap.

Start cap placement by measuring head circumference to choose the proper cap size. When placing the cap have the subject sit up straight, hold their chin up, look ahead, and

try to remain still. If participants dip their head during application the EEG net will not be seated properly. Next measure to ensure the cap is centered; this is normally done by ensuring that the vertex sensor Cz is positioned halfway between both the nasion and the inion and the two pre-auricular points. Some EEG systems, typically those that use conductive gel, require exfoliation of the scalp underneath each sensor during application. This is done to improve impedances by removing skin oils, dead cells, and any hair that might be in the way. Abrasion should be very gentle; a breach of the skin presents an unacceptable infection risk and must be avoided completely.

During the experiment, subjects should be asked to try to stay relaxed, so as to avoid muscle artifacts. Taking breaks after every 10–15 minutes of recording time will help prevent fatigue from setting in. As blinks are a major source of artifact in the EEG, it can be helpful to include a short time window at the end of each trial for subjects to blink, thereby avoiding contamination of the stimulus period. When recording EEG, the experimenter should not attempt to multitask (reading articles, writing grants, etc.) but instead monitor the data quality. This allows any issues to be noticed and addressed during the session without having to resort to statistical artifact removal later on.

While the above suggestions are valid in most cases, additional considerations must be taken into account when running special subject populations, such as children or clinical populations. When running children, it is necessary to have at least two experimenters present in order to ensure safety and mind any siblings that may be present. It may be helpful to have some children's toys present in such situations. Younger toddlers may attempt to tear off the cap; do not allow this. Instead have an experimenter remove the cap if it becomes troublesome to the child. During the capping process of an infant, one experimenter should place the net while the other keeps the baby's attention. Solid cap placement is important here, as the limited attention span of special populations prevents extensive adjustments; it has to be correct on the first try. Babies and children should be given a few minutes to adjust to the sensation of the cap and, with a little distraction, they often quickly forget it is there. In addition to normal monitoring of the EEG, these subjects will need constant monitoring to ensure that there are no problems during recording. A video camera and monitor setup may be helpful in this regard.

Infection is the primary safety risk for EEG; therefore it is imperative that the net and any other reusable equipment be disinfected between each use. An EEG session cannot be run without this step. Always follow manufacturer guidelines regarding disinfection of the EEG net, which will usually involve soaking it in a specific disinfectant solution. To help avoid infection, EEG should not be run on anyone with open wounds on the scalp or excessive nasal drainage.

Impedance

Impedance is a measure of the connection quality between the EEG sensors and the scalp; it can be thought of as the AC correlate of resistance. Good impedances are essential to a quality recording and should therefore be kept below an appropriate threshold for the session. Low-impedance gel-based systems will typically aim for impedances of 5–10 kΩ while some higher impedance saline systems may use values of 50–70 kΩ. Regardless of the system selected, steps can be taken to keep impedance low. These

include exfoliation of the skin when applying the cap and using cotton-tip applicators or a similar tool to gently brush the hair out of the way and ensure the electrode is in direct contact with the scalp. The subject should remove any facial makeup before placement of the net if sensors sit on the cheek. Additionally, before the day of the session the subject should be asked to avoid using conditioner, hair gel, or other such products as these too may negatively affect signal quality.

Referencing

EEG measurements must reflect the difference in activity between two or more electrode sites. EEG recordings can be either bipolar or monopolar. Bipolar recordings reflect the difference in electrical potential between a pair of electrodes. Bipolar recordings are useful for comparing areas on the right and left side of the head and are used primarily in clinical settings. In monopolar recordings, the potential of each electrode is compared to a neutral electrode or the average of all electrodes (average reference). Relatively neutral sites for a reference include, for example, the ear, mastoid, or nose. Alternatively, electrodes on both ears may be linked together as if they were one electrode centered on the head and used as a reference—known as a linked-ear reference. Any linked averages should be performed offline through re-referencing. An average reference is the mathematical average of activity at all EEG electrodes. The average reference may come the closest to a neutral site because, theoretically, activity in opposing dipoles may cancel each other out (however, this is not often the case as there are no electrodes placed underneath the head). Each possible reference has advantages and disadvantages. Although selection of a reference site is an important consideration, online reference choice is somewhat arbitrary because it is possible to re-reference data offline.

Amplifier

The EEG signal is extremely small; in order to be viewed it requires amplification. The amplification factor, called the gain, will likely range from 1,000–100,000 depending on the amplifier model. As described previously, EEG measures voltage, which is a relative signal that reflects the difference between an active electrode and the reference site. However any noise inherent in the reference site will also be picked up. To avoid this, most amplifiers are differential, meaning that the signal they amplify is the difference between the amplifier and the reference subtracted away from the common ground. To understand common mode rejection, imagine three electrode sites: one reference, one common ground, and one active electrode. A differential amplifier measures the signal between each active electrode and the common ground and the signal between the reference and the common ground. The difference between these two signals is taken, resulting in the signal from the common ground being canceled out, leaving only the difference between the active electrode and the reference. It is this difference that is then amplified and sent to the recording computer. As a result of this process, noise common to the ground reference electrode is subtracted out from the data leading to a cleaner recording with significantly reduced noise. The higher the common mode rejection, the better the amplifier is at reducing noise. An amplifier must be capable of handling all

input values it receives without incident; for this reason an amplifier of 20 or 24 bits of resolution is recommended.

Sampling rate

The EEG recording is an analog signal consisting of voltage deflections across time and therefore must be digitized before it can be stored on a computer. This is accomplished by taking a series of discrete samples from the continuous data. The rate at which these samples are taken is the sampling rate of the EEG and effectively defines the temporal resolution of the data. The essential factor to consider when choosing a sampling rate is the Nyquist theorem. This theorem states that in order to accurately reconstruct all the information in the original analog signal, the EEG must be digitized using at least twice the rate of the maximum frequency in the signal. If the sampling rate chosen is lower than this, low-frequency noise (aliasing) will be introduced into the recording. Since most brain-related activity is below 100 Hz in frequency, a sampling rate of at least 200 Hz should be used to prevent aliasing. In practice, many researchers prefer to sample more frequently than the Nyquist theorem requires, thereby improving the EEG signal-to-noise ratio. Once this consideration is satisfied, there are a variety of sampling rates to choose from. Some common sampling rates include 250 Hz, 256 Hz, 500 Hz, and 1,000 Hz. Other factors to consider when selecting a sampling rate are file size and diminishing returns. With regard to the former, higher sampling rates will produce larger datasets that require more space to store and more time to analyze; although modern 64-bit machines should not have great difficulty with this, it may present an unaffordable financial cost in terms of computer hardware. Additionally, as the sampling rate increases, diminishing returns begin to reduce the benefit gained with a higher rate. Sampling rates above 2,000 Hz are unlikely to provide much added advantage.

While any sampling rate between 500 and 2,000 Hz should suffice for the majority of experiments (Cohen, 2014), 1,000 Hz is perhaps the most convenient and conceptually simple as each sample point will correspond to 1 ms. It is recommended to select 1,000 Hz or another high value as the sampling rate. This is because, should storage space or other computer resource limitations become a problem, there is always the option of down sampling (reducing) a high sampling rate after recording. Many EEG software packages will include an option to perform this operation, and it is preferable to reduce a sampling rate to something manageable rather than losing information to aliasing.

Filtering

Filtering is a pre-processing step that is used to remove unwanted frequencies from the recording. Filtering operates by first transforming the EEG time series into the frequency domain, then applying a function that removes undesired frequencies. Once these frequencies are removed, the data is transformed back into the time domain. It is helpful to note that filtering of the EEG waveform does not function in the same manner as a water or air filter. Instead of being like a sieve, EEG filtering is a mathematical operation applied to a dataset that attenuates the power of frequencies outside a specified threshold. For example, if the threshold is set at 50 Hz, it might be expected that

all activity greater than 50 Hz would be cut off while activity below this point would be preserved. In reality, however, filters do not have sharp cutoffs right at threshold, but instead slope as they approach the threshold value. Thus, in the example given, the filter might start to mildly suppress frequencies at 48 Hz and gradually increase until maximal attenuation is reached at 50 Hz. In other words, filtering involves a controlled distortion of the data. Improperly applied filtering may result in shifted phase or latency values and yield incorrect results. For this reason caution must be used when applying any filter.

In general, filters are applied to EEG for the purpose of removing artifactual frequencies from the signal or to be able to visualize the data. Artifactual frequencies will likely consist of high-frequency muscle noise or line noise signals from electronic equipment and very low-frequency drifts arising from scalp potentials during recording. These scalp potentials make it difficult to visualize the EEG without filtering.

Filters may be divided into four categories: high-pass, low-pass, band-pass, and notch. High-pass filters remove frequency activity below their set threshold; the name comes from the fact that they "pass" through the higher frequencies unaffected. For example, a 0.1 Hz high-pass filter removes frequencies below 0.1 Hz and retains those above. Similarly, a low-pass filter at 40 Hz would remove frequencies above threshold while passing those below. A band-pass filter is simply a combination of high- and low-pass filters into a single filter instead of applying each separately. In most cases, EEG will be band-pass filtered. Notch filters attenuate the signal around a specific frequency, such as 60 Hz, and are sometimes used to remove line noise.

In the majority of cases, filter settings should be focused on suppressing very low frequency drifts and filtering out high-frequency noise. A band-pass setting of 0.1–100 Hz for healthy adult subjects should be sufficient in most cases and is a good conservative parameter to avoid unnecessary distortions. Those who wish to examine very high frequencies may use an upper limit of 200 Hz or even omit the low-pass filter altogether, with the caveat that this will produce noisier waveforms. Low-pass filters are less distortionary in nature than high-pass filters. In light of this, some studies that examine ERPs will set the upper edge of the band-pass filter to 30 or 40 Hz; these values will produce cleaner looking ERPs by removing any high-frequency noise while leaving the properties of the ERP unaffected. High-pass values greater than 0.1 Hz should normally be avoided as they will alter the latency of some ERP waveforms and change the results of the experiment.

When recording EEG from subject populations where movement or other artifacts will be common, more restrictive filter settings may be used. For example, a band-pass of 0.5–30 Hz would be appropriate when recording data from infants. In such cases the distortion caused by the high-pass setting may be justified by the exclusion of low-frequency noise. Line noise, present at 50 or 60 Hz, depending on geographical region, is another reason filtering may be required. Using a notch filter is not recommended due to the risk of distorting the data; ideally line noise sources should be eliminated before recording. If it is still necessary to remove line noise, use a lower low-pass cutoff (e.g., 40 Hz) or an artifact correction technique such as sliding window multitapers or ICA before turning to a notch filter if possible.

Normally the EEG amplifier incorporates an online anti-aliasing filter at the hardware level. This should be used in accordance with manufacturer recommendations. Aside

from this often built-in feature, EEG data should not be filtered online. Filters should be applied offline to continuous data files that are not segmented by condition (epoched) to avoid edge artifacts. The filter used should be noncausal to avoid latency shifts in the data. When learning about filters it may be helpful to filter the same dataset using multiple settings and then examine the results to see what differences exist. When in doubt about what settings to use, it is safe to default to a 0.1–100 Hz band-pass.

Pre-processing of data

Artifacts are variations in EEG signal that originate from nonneural sources. It is a problem when artifacts are misinterpreted as EEG data. Sources of artifacts include line noise from recording equipment and biological signals including eye blinks and movement, muscle activity, cardiac activity, movement of the lips and tongue, and skin potentials. One way to reduce these artifacts is to ask the subject to relax facial muscles and minimize head and eye movements during recording. However, instructions to suppress movement may result in a secondary task, associated with brain activity that may interfere with the EEG signal of interest. Because many biological artifacts are distinctive in signal and appearance (e.g., electromyographic activity is usually greater in amplitude than EEG signals of interest), sophisticated analysis programs include algorithms to remove these signals from the EEG. A common nonbiological source of noise is line noise interference, usually at 50 or 60 Hz. This noise may emanate from fluorescent light fixtures or stimulus devices such as computer monitors. One solution is to turn off these devices. However, if the room is too dim, the researcher runs the risk of producing an environment conducive to sleeping. Other solutions include correcting line noise after data has been collected using tools within the data analysis software.

According to Luck (2014), there are several ways in which artifacts may negatively affect EEG recording. First, artifacts reduce the signal-to-noise ratio. Thus, one may be unable to find differences between experimental conditions in the averaged EEG waveform. Second, some artifacts occur systematically and may be time-locked to stimulus onset. For example, participants may tend to blink systematically after image presentation, resulting in a blink artifact that appears time-locked to the image presentation over many epochs. This is problematic when the artifact occurs in one condition more than other conditions and is not eliminated by averaging the waveform. Finally, eye movements and blinks during presentation of visual stimuli could result in differences in perception of the images. A systematic difference in ocular activity between conditions could present a confound.

Rejection and correction of artifacts is necessary before analysis to reduce noise from nonbrain sources. Pre-processing allows for the offline reduction of artifacts in the EEG recording. A researcher may use either manual or automatic procedures—or a combination of both—for artifact rejection. There are trade-offs to either approach. Visual inspection, a manual procedure, is tedious and subject to human error. An automatic procedure may either fail to reject artifacts or reject data of interest based on the stringency of the parameters. One may prefer a semi-automated approach, in which both methods are employed. A helpful automatic procedure is independent components

analysis (ICA), a blind source separation technique that decomposes the EEG signal into individual source signals. ICA yields a series of components, each of which represents an independent source extracted from the EEG data and, when summed, constitute the original signal. Once sources have been pulled out from the data they can be examined and large, consistent artifacts such as blinks or EMG will be isolated into components that can be subtracted from the dataset. Doing so eliminates the noise signal from the EEG without affecting the other components; this way artifacts can be removed without having to cut out channels or epochs.

An example pre-processing sequence for a single subject of an ERP study includes filtering the continuous data, epoching data, manually identifying and removing bad channels and epochs, conducting an ICA to identify potentially bad components, manually inspecting and rejecting bad components, re-referencing electrodes using an average reference, interpolating deleted channels, separating epochs by condition, removing baseline, and (finally!) looking at the ERPs.

EEG research in media contexts

Although some media researchers have used EEG to investigate phenomena, there are some challenges to using EEG in a media environment, especially if one wishes to examine ERPs. For example, investigation of ERPs is more conducive to research with simple, rather than complex, stimuli (e.g., still images rather than video). The necessity of averaging over many trials to examine ERPs may also be prohibitive. Participants may habituate to stimuli or become fatigued if the procedure lasts a long time. However, EEG should not be discounted as a measure to use in media research. Potter and Bolls (2012) state that "EEG is currently an example of a psychophysiological measure that is on the brink of providing breakthrough scientific insight into the dynamic interaction between the human brain and media content" (pp. 98–99).

Despite the challenges, some media researchers have been able to examine ERPs. Treleavan-Hassard and colleagues (2010) examined the P3 in response to brand logos. Logos were presented in blocks of 10 while EEG data were collected. Four of the logos appeared later in advertisements within television programs. Of these, two were presented in banners at the top of the screen that participants could interact with while content continued to play (Impulse ads). The other two logos were also presented in banners at the top of the screen but participants were directed away from the content on the screen when they interacted with these banners (Dedicated Advertiser Location ads). Participants viewed the logos again while EEG data were collected. In response to logos contained in the Dedicated Advertiser Location ads, latencies of P3 were shorter post-interaction than pre-interaction. Latencies of P3 did not differ between pre- and post-interaction exposure for logos within Impulse ads. The authors concluded that automatic attention was greater for the Dedicated Advertiser Location Ads compared to the Impulse ads.

Because of the challenges of conducting ERP research in media contexts, much of the existing research investigates the presence or absence of certain frequency bands. For example, one study demonstrated that alpha activity during commercials is negatively

correlated with recognition and recall of elements in the commercial (Reeves et al., 1985). Another study, using alpha power as a measure of cortical arousal, examined hemispherical asymmetry in processing of emotion on television. Results indicated that the right hemisphere had lower alpha power in response to negative scenes while the left hemisphere had lower alpha power in response to positive scenes (Reeves, Lang, Thorson, & Rothschild, 1989). More recently, Minas and colleagues (2014) examined the presence of alpha activity over different locations of the scalp to examine information processing during a discussion with a virtual team.

Frequency band research is not limited to the investigation of alpha. Kretzschmar and colleagues (2013) examined theta band activity—associated with memory encoding and retrieval—while adults read text on paper, an e-reader, or a tablet. They found that theta band activity did not differ between devices for young adults. Older adults, however, demonstrated reduced theta voltage density and shorter mean fixation durations while reading text on a tablet, compared to reading text on an e-reader or on paper. Comprehension of the text for both older and younger adults did not differ between reading media. The authors concluded that older readers benefitted from the contrast provided by the backlit text of a tablet.

Some limitations of EEG

EEG has many advantages for the media researcher, many of which are listed above. However, compared to other neuroimaging techniques there are some limitations as well. Specifically, although EEG provides high temporal resolution, it lacks spatial resolution. Thus, a researcher using EEG will be able to determine the time course of electrical activity in the brain with high precision, but will not be able to determine where in the brain that activity originated—an issue known as the inverse problem. In addition, although the tissue between cortical neurons and the scalp acts a conductor, EEG is unlikely to pick up activity from deeper brain structures.

A study that uses EEG techniques requires thoughtful consideration of design. Because EEG typically requires the use of many trials of stimuli, a media researcher interested in studying a single message or a limited set of messages may be prohibited from using this technique. Depending on the length of stimulus presentation, many trials of stimulus presentation in multiple conditions can create an experiment that lasts for a considerably long time. Many trials of audiovisual stimuli that last for 30 seconds or longer (e.g., advertisements) may result in an experiment that is too long for the comfort of a participant who is required to remain relatively still. Before the experimental session, obtaining acceptable impedances for many electrodes may take a substantial amount of time—sometimes 20 minutes or longer. Long experiments may result in the drying out of gelled or saline-soaked electrodes and will need to be broken into blocks. In between these blocks researchers will need to check and regain acceptable impedance levels. EEG is not only time-consuming in the data-collection phase of an experiment; it is also time-consuming in the pre-processing phase. Pre-processing of data can take a substantial amount of time to complete—usually several hours for each participant.

SEE ALSO: Experiment, Laboratory; Measurement of Attitudes; Measurement of Cognitions

References

Adrian, E. D., & Matthews, B. H. C. (1934). The Berger rhythm: Potential changes from the occipital lobes in man. *Brain*, *57*, 355–385. doi:10.1093/brain/57.4.355

Bartholow, B. D., & Amodio, D. M. (2009). Using event-related brain potentials in social psychological research. In E. Harmon-Jones & J. Beer (Eds.), *Methods in social neuroscience* (pp. 198–232). New York: Guilford Press.

Berger, H. (1929). Ueber das Elektrenkephalogramm des Menschen. *Archives für Psychiatrie Nervenkrankheitren*, *87*, 527–570.

Cohen, M. X. (2014). *Analyzing neural time series data: Theory and practice*. Cambridge, MA: MIT Press.

Cook, I. A., O'Hara, R., Uijtdehaage, S. H. J., Mandelkern, M., & Leuchter, A. F. (1998). Assessing the accuracy of topographic EEG mapping for determining local brain function. *Electroencephalography and Clinical Neurophysiology*, *107*, 408–414. doi:10.1016/S0013-4694(98)00092-3

Donchin, E. (1981). Surprise! … Surprise? *Psychophysiology*, *18*, 493–513. doi:10.1111/j.1469-8986.1981.tb01815.x

Goldman, R. I., Stern, J. M., Engel, J., & Cohen, M. S. (2002). Simultaneous EEG and fMRI of the alpha rhythm. *NeuroReport*, *13*, 2487–2492. doi:10.1097/00001756-200212200-00022

Kretzschmar, F., Pleimling, D., Hosemann, J., Füssel, S., Bornkessel-Schlesewsky, I., & Schlesewsky, M. (2013). Subjective impressions do not mirror online reading effort: Concurrent EEG-eyetracking evidence from the reading of books and digital media. *PLoS ONE*, *8*. doi:10.1371/journal.pone.0056178

Luck, S. J. (2014). *An introduction to the event-related potential technique*. Cambridge, MA: MIT Press.

Minas, R. K., Potter, R. F., Dennis, A. R., Bartelt, V., & Bae, S. (2014). Putting on the thinking cap: Using NeuroIS to understand information processing biases in virtual teams. *Journal of Management Information Systems*, *30*, 49–82. doi:10.2753/MIS0742-1222300403

Potter, R. F., & Bolls, P. D. (2012). *Psychophysiological measurement and meaning: Cognitive and emotional processing of media*. New York: Routledge.

Reeves, B., Lang, A., Thorson, E., & Rothschild, M. (1989). Emotional television scenes and hemispheric specialization. *Human Communication Research*, *15*, 493–508. doi:10.1111/j.1468-2958.1989.tb00196.x

Reeves, B., Thorson, E., Rothschild, M., McDonald, D., Hirsch, J., & Goldstein, R. (1985). Attention to television: Intrastimulus effects of movement and scene changes on alpha variation over time. *International Journal of Neuroscience*, *25*, 241–255. doi:10.3109/00207458509149770

Stern, R. M., Ray, W. J. & Quigley, K.S. (2001). *Psychophysiological recording* (2nd ed.). New York: Oxford University Press

Sutton, S., Braren, M., Zubin, J., & John, E. R. (1965). Evoked-potential correlates of stimulus uncertainty. *Science*, *3700*, 1187. doi:10.1126/science.150.3700.1187

Tanaka, J. W., & Curran, T. (2001). A neural basis for expert object recognition. *Psychological Science*, *12*, 43–47. doi:10.1111/1467-9280.00308

Treleaven-Hassard, S., Gold, J., Bellman, S., Schweda, A., Ciorciari, J., Critchley, C., & Varan, D. (2010). Using the P3a to gauge automatic attention to interactive television advertising. *Journal of Economic Psychology*, *31*, 777–784. doi:10.1016/j.joep.2010.03.007

Walter, W. G., Cooper, R., Aldridge, V. J., McCallum, W. C., & Winter, A. L. (1964). Contingent negative variation: An electric sign of sensori-motor association and expectancy in the human brain. *Nature*, *203*, 380–384. doi:10.1038/203380a0

Further reading

Beatty, M. J., Heisel, A. D., Pascual-Ferrá, P., & Berger, C. R. (2015). Electroencephalographic analysis in communication science: Testing two competing models of message production. *Communication Methods & Measures*, *9*(1/2), 101–116. doi:10.1080/19312458.2014.999753

Harmon-Jones, E., & Peterson, C. K. (2009). Electroencephalographic methods in social and personality psychology. In E. Harmon-Jones & J. Beer (Eds.), *Methods in social neuroscience* (pp. 170–197). New York: Guilford Press.

Ravaja, N. (2004). Contributions of psychophysiology to media research: Review and recommendations. *Media Psychology*, *6*, 193–235. doi:10.1207/s1532785xmep0602_4

Stern, R. M., Ray, W. J., & Quigley, K. S. (2001). *Psychophysiological recording* (2nd ed.). New York: Oxford University Press.

Glenna L. Read is a doctoral candidate at Indiana University. She has a background in experimental psychology and her area of interest can be broadly described as media psychology. Research interests include the social, cognitive, and neurological processes involved in the perception of media messages and how these processes influence and relate to stereotyping and prejudice.

Isaiah J. Innis is an EEG technician at Indiana University. He has a background in eyeblink conditioning and EEG microstates. He is involved in research on a variety of topics including the structure of language and the perception of biological motion.