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SYSTEMATIC REVIEW

STUDYING THE SWALLOW USING SURFACE ELECTROENCEPHALOGRAPHY: A SYSTEMATIC REVIEW

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Abstract

Background: Swallowing is an important function for life sustenance but our understanding of its neural organization in the human cortex is not yet fully explored. Electroencephalography is a functional neuroimaging modality that already has and could further contribute to that direction. In this review, we have sought to gather and present findings from studies that used the EEG on healthy individuals for the investigation of the cortical mechanisms that moderate deglutition.

Methods and Materials: Four databases were searched for studies that used the EEG as their main research modality on healthy individuals and administered various stimuli for them to swallow. The risk of bias assessment of the studies was conducted using the NIH rating scale for observational studies.

Results: Our search yielded 393 studies in total and nine of them were included in the final discussion. The risk of bias assessment showed good quality of the studies. The nine studies were presented in a table following an adapted PICOS outline depicting the population, the comparisons, the means of measurement and the outcomes.

Conclusions: Researchers studied the morphology of the signal before, during and after the swallow and its discrepancies in frequency in relation to stimuli alterations. Discrepancies in methodology and concordance with previous research are discussed.

Keywords: Swallowing, EEG, adults, healthy, deglutition, neural response.

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INTRODUCTION

Swallowing is a complicated function that humans perform several times, every day. Many structures of the head and neck are involved in it and at the same time, certain events take place in the cortices. While we have learned much in the past few years through rigorous research, there is much that we need to uncover.

The neural control of swallowing is a complex one with afferent and efferent neurons carrying information to and from the brain and central pattern generators (CPGs) bypassing the cortex and giving rhythmic motor output to aid the swallowing process.[1]

After decades of research, it has been shown that even in the most reflexive stages (the pharyngeal and oesophageal) there is still some cortical input moderating the CPGs generated by the brainstem.[2]

These central pattern generators for swallowing and chewing do not negate the need for cortical input for the moderation of the swallowing process.[2] The mechanisms involved in the exchange of cortical and bulbar information regarding swallowing are still unclear.[3] It has been demonstrated that cortical input is needed for the mastication and the pharyngeal swallow of a bolus to moderate the motor activity produced by the CPGs.[2,4]

One method to investigate brain functions is electroencephalography (EEG). It was firstly introduced in the 19th century by Hans Berger, a psychiatrist, although it was discovered some years earlier by Richard Caton.[5] Since then, it has been greatly used in surgery as well as for the understanding of epileptic seizures, sleeping problems and other neurogenic disorders.[5]

During an EEG, macroscopic electrodes are placed on the surface of the scalp and detect electrophysiologic activity from the cortical regions underneath them.[6] More specifically, EEG electrodes detect the summation of postsynaptic potential generated by groups of pyramidal cells that are positioned perpendicularly to the scalp.[7] This potential travels isotropically through the layers of the cranium until it reaches the outer layer of the scalp and the conductive electrodes.[6]

Hardware choices include portable headsets and caps, wired or wireless for use in more functional activities and with wet or dry electrodes. There has been much interest lately in the use of wireless headsets in the context of Brain-Computer Interface (BCI) networks for academic research and rehabilitation purposes.[8]

The advantages of the EEG in research and clinical practice makes it an ideal means for the understanding of the neurophysiology of certain events. Also, it can be a useful tool in the investigation and diagnosis of the pathophysiological mechanisms of diseases. Such an effort has been made for the study of the swallowing mechanism.[9] The outcomes of this attempt are very important as they can give insight into the underlying networks that control this function and thus, solutions in the rehabilitation of its pathologic manifestation, dysphagia.

Two previous reviews were identified, one by Jestrovic et al.[10] and one by Bhutada et al.[11] In the first review, authors analysed the different methodologies employed in the investigation of cortical potentials evoked in different aspects of swallowing and motor-imagery of swallowing, both with traditional and advanced EEG analysis. What that review lacked was a quality assessment of the articles. Also, the review was published in 2015 and since, more research has been published on this area. The second review focused on Event Related Potentials (ERPs) and included articles that studied adults with and without dysphagia whereas this review only refers to research done on healthy adults, without dysphagia. One more difference is that we did not limit our search to articles focusing on ERPs and we only included research which employed boluses as stimulation of the cortex and not mechanical or electrical stimulation of the pharynx.

AIM

This review aimed to compile and analyse studies that used surface electroencephalography to detect cortical signals related to swallowing. Through this analysis, we aimed to explore the methodologies used in EEG signal detection of the swallowing movement, the components on which researchers focused and to evaluate and compare the results with previous knowledge from brain imaging studies which used different modalities.

METHODS

This systematic review was conducted according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis statement (PRISMA).[12]

Four databases, PubMed, Cochrane, Web of Science and OpenGrey, were searched for trials concerning the use of EEG in the study of swallowing. Due to the nature of the stimuli and the imaging technique, only observational studies qualified for inclusion in the review. Only studies with healthy participants were considered for inclusion as we wanted to review the electroencephalographic representation of normal swallowing and not of dysphagia or in the context of other pathological entities. The search stream was the following: (electroencephalogram OR electroencephalography OR electroencephalographic OR eeg) AND (swallow OR swallowing OR deglutition).

There was no limitation on the date of publication and no additional filters were used. We opted for studies that included healthy adult subjects and used surface electroencephalography as the main modality and means of measurement. To be considered for inclusion, the stimuli that researchers used should have been specifically swallowed and not applied directly to the pharynx and they could be anything, from dry swallows to solid foods. Each database was searched separately, and all results were pooled in a bibliography management program where duplicates were identified and eliminated.

The assessment of the risk of bias was conducted with the use of the NIH quality assessment tool for observational case series studies.[13] For the grading of the items the responses "Yes", "No", "Not Applicable", "Not Reported" and "Cannot Determine" were used.

RESULTS

Initially, 393 records were identified after searching the four databases mentioned previously and were pooled in a bibliography management program for further inspection. Nine articles qualified for inclusion in the review. One more article was added later, after a second, confirmatory search increasing the number of included studies to ten. The flow chart of the study selection process can be found in Figure 1.

In summary, the quality of the studies was considered good all studies scoring above average. Also, there was a degree of uniformity in the ratings as the items that had been rated with "No" or "Not Reported" were mostly the same among studies. The mean of the total scores from the studies evaluated was 7/9. Analytic information about quality assessment can be found in Table 1.

Although all articles included studied the healthy swallow during electroencephalography, each of them concerned themselves with somewhat different subparts of the process making it difficult to review the data as a whole and making comparisons. The studies were thus categorized into four groups according to the specific study outcome: movement-related cortical potentials, mu event-related desynchronization/synchronization, stationarity and brain networks.

In terms of population, the smallest sample was found in the study carried out by Hiraoka[14] in which 7 people were included. In the rest of the studies, the sample ranged from 15-55 healthy participants, aged 18-65 years.

Many disparities were found in the controls used in each study. The most consistent trials were observed in 3 of the studies carried out by Jestrovic's team [15–17] with the swallowing of five different stimuli. All other studies used different tasks and stimuli to investigate swallowing under various conditions.

Differences were also observed in the paraphernalia used. Electrode number varied from 3 to 68. Also, the number of devices used to distinguish the interferences from other bodily functions like breathing or eye movements from the main event ranged greatly from none to several sensors mounted in the head and neck area.

Probably the most important differences are those of the outcomes. These studies had quite different goals and thus comparison of their collective outcomes was not possible. To overcome this, we divided them into groups, as stated above, wherever possible to compare similar results.

Three of the studies[14,18,19] studied the movement related cortical potentials or MRCPs which are associated with movement and are referenced to pre and post movement action potentials.[20] In these studies, research focused on the components of the

Bereitschafts potential which reflect planning of movement in the supplemental motor and primary motor areas of the cortex.[21]

Two studies[22,23] focused on retrieving event related synchronization/ desynchronization (ERS/ERD) of the mu rhythm. Mu rhythm presents with two components, alpha and beta, both correlating with sensorimotor activity.[24]

ERD/ERS are used to depict the decreases or increases in signal respectively. The information that derives when assessing ERD/ERS during a task is the time-frequency correlates to that movement. Mu ERD/ERS correlates with an increased thalamocortical excitation during motor observation, preparation and execution.[25]

The stationarity of the signal during swallowing was studied by Jestrovic et al. (15). A signal is defined as stationary *"if a signal's statistical characteristics do not vary over time"*.[26] EEG signal is inherently non-stationary as events change the neuronal activity over time and that is recorded as signal variations.

Lastly, four studies[16,17,27,28] explored the connectivity patterns of the networks responsible for swallowing and their efficacy. Functional connectivity refers to *"how neural activity in one brain area relates to activity in another"*.[29] A brain network is a collection of brain areas that are interconnected functionally to accomplish a certain activity.[30] A network that presents with small world properties is considered to be optimally organized, with high local clustering and short path length that promote communication between nodes.[31] Summarized details of the results can be found in Table 2 in the appendix.

DISCUSSION

The most interesting outcomes of the studies in this review were that electroencephalographic signals of swallowing share similarities with those of other body movements, that different stimuli can alter the waveform of cortical potentials with observable differences and that brain networks above the stem have an optimal organisation and important role in the moderation of swallowing suggesting – as it has been demonstrated already in the literature - that swallowing is not an automatic, reflexive movement.

The earliest works identified by this review,[14,18,19] investigated the movement related cortical potential or MRCPs and its components. These studies focused mainly on the Bereitschafts potential or BP, the Contingent Negative Variation or CNV and the Motor Potential MP.

MRCPs in pre motor volitional activity were observed in all three studies with absence of the Negative slope[14,18] or greatly reduced amplitude.[19] The early component of the Bereitschafts potential was found before the onset of movement as happens with motor action of other parts of the human body but its late component was not found in two of the three studies. In the third study, it is not clearly stated whether a late component was found.

Researchers argued that possible explanations for this absence are either a total cessation of cortical activity milliseconds before movement onset or the immigration of the signal to regions not recorded with surface EEG.[14,18,19] We also speculated that this inability of detecting part of the potential might be due to methodological processes of signal acquisition and clearing. Also, since EEG can detect activity from dipoles positioned perpendicularly to the electrodes,[7] any activity that occurs with a different orientation or in structures deep within the brain cannot be recorded.

Another point of interest for two of the studies[14,18] was the exploration of laterality in volitional swallow MRCPs. Both found no significant laterality of the pre-movement potentials. Previous studies have showed a certain lateralization of the signal, not specifically at the point of movement preparation but rather vaguely along the swallowing process.[32,33] What is noted by Huckabee's group is that a pattern of non-significant lateralization was traced in the 250 ms prior to movement onset. A more recent study by Toogood et al.[34] investigating the cerebral contribution to the swallowing process, did not find any lateralization.

The next two studies included in this review are those conducted by Cuellar et al.[22] and Koganemaru et al.[23] The first study found mu components in the majority of the sample, bilaterally with a right predilection suggesting stronger right sensorimotor involvement. The components found were localized with two different types of analysis in two different but adjacent structures, the premotor and the primary motor area. These findings, though equivocal, are in accordance with previous research suggesting that mu components are found both in the premotor and primary motor areas.[35] The second study found ERD bilaterally in frontal and parietal areas in the beta band.

Another field that drew researchers was the effect that swallowing has on the stationarity of the EEG signal during swallowing.[15] The signal produced by swallowing was shown to be non-stationary and result suggested no effect of age on the signal yet significant differences for the rest of the parameters which were gender, age, brain regions and bolus viscosity. More specifically, almost all compared viscosities presented with significant differences in mean and variance which demonstrates that viscosity did influence the stationarity of the signal. The non-stationarity of the signal increased proportionally to viscosity increase. The only consistencies that did not present with great discrepancies were nectar when compared to honey-thick fluids.

There was no clear evidence in recent literature as to the effect of the viscosity on cortical activation though some studies that compare water to saliva swallows report greater activity in the water condition.[36,37] Among the studies reviewed here, the one by Hiraoka[14] also demonstrated greater activity during saliva swallow as opposed to water consumption. Taking into account the viscosity of these two substances, 1 cP for water and 1.05/1.29 cP for saliva,[38] these results probably contradict the ones by the Jestrovic team as they imply that lower viscosity substances inflict greater cortical activity than the ones with higher viscosity.

The last 4 studies included in this review have sought out to investigate functional connectivity and brain networks during swallowing using different stimuli and head positions.[16,17,27,28] showed was that there are many changes in the swallowing mechanism occurring when different stimuli are introduced. These rather external changes could potentially also cause internal changes as well affecting brain organization and neuronal communication.

The studies that investigated network architecture, showed optimal brain organization with common differences amongst them in the Alpha and Gamma frequencies suggesting alterations in inhibition and muscle recruitment during swallowing while one of them also found a difference in Beta frequency implying cognition alterations. As for the viscosities, the brain organization became more optimal as the fluids were thicker probably resulting from changes in the sensory information.

One of the studies also investigated the effects of consecutive swallows to the brain activity and found different brain networks between consecutive swallows whereas a study conducted by Kleinjan & Longeman[31] in 2001 showed no great differences between consecutive swallows in young adults in swallow physiology assessed via videofluoroscopy, a results contradicting the aforementioned finding.Lastly, one study tried to relate brain organization with bolus volume and attention. And associated different brain networks are for each condition investigated.

As all research, these studies also present with certain limitations. The most prominent is that researchers did not randomize the order of stimuli and conditions. Participants could foresee the next stimulus or task and that could affect their reactions, preparation and execution and thus the electrophysiological signal. Some studies also used few EEG electrodes which might have affected the measurements. Apart from the number of EEG electrodes, it is important to take into consideration the sEMG electrodes used If these are too few, there may be weaker associations of muscle to cortical activity which will affect the conclusions drawn.

Another important limitation found in some of the studies was the lack of meticulous bolus measurement and calibration of the physical characteristics of the boluses (e.g. taste and rheology). As different stimuli induce different reactions in the signals, it might make a great difference in the results and associations knowing the actual properties of every stimulus.

CONCLUSIONS

This review showed that there has been an interest in recent years to explore the human swallow through electroencephalography and map the cortical responses it ensues. Research parties have tried to investigate the swallow using various methodologies and have associated their results with studies that have used modalities such as MEG or fMRIs.

Future studies should try to eliminate some shortcomings and also focus on implementing methodologies that measure more precisely the stimuli administered and their specific characteristics and properties. What that could accomplish is a deeper understanding in the effect of those boluses in the swallowing process and their value when used during therapy of swallowing difficulties. Moreover, apart from the healthy individuals, it would be interesting to research cortical potentials in disordered swallowing and what differences they present when compared to healthy deglutition. This may give us diagnostic information and help with the advancement of therapeutic techniques to treat more efficiently dysphagia.

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ANNEX

Figure 1. Preferred Reporting Items for Systematic Reviews and Meta-Analysis Flow Diagram for Study Selection (PRISMA Flow Diagram) – modified (13).

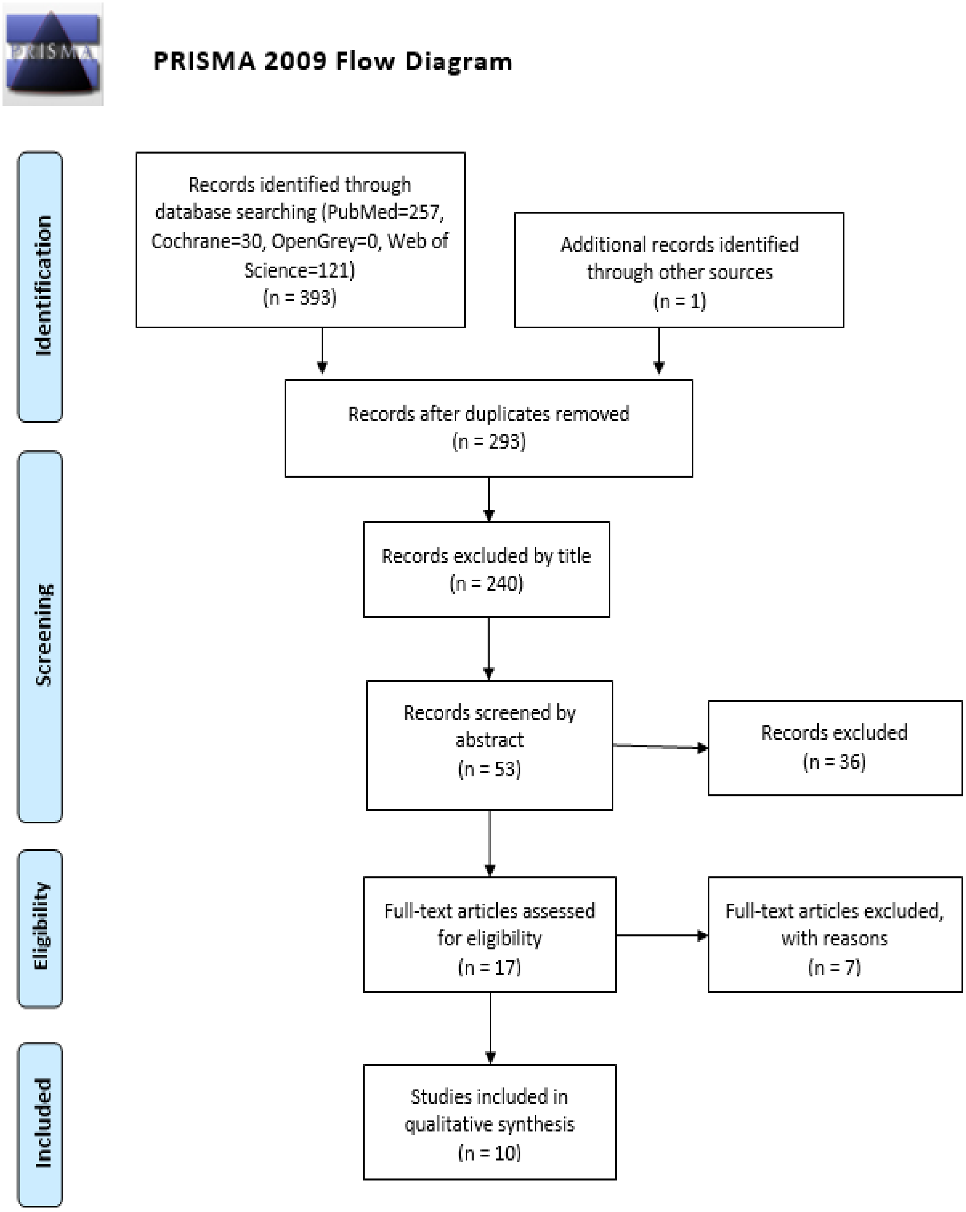

Table 1. NIH Quality Assessment Tool for Case Series Studies. Q1. Was the study question or objective clearly stated. Q2. Was the study population clearly and fully described, including a case definition. Q3. Were the cases consecutive. Q4. Were the subjects comparable. Q5. Was the intervention clearly described. Q6. Were the outcome measures clearly defined, valid, reliable, and implemented consistently across all study participants. Q7. Was the length of follow-up adequate. Q8. Were the statistical methods well-described. Q9. Were the results well-described.; CD, cannot determine; NA, not applicable; NR, not reported.

	Q1	*Q2*	*Q3*	*Q4*	*Q5*	*Q6*	*Q7*	*Q8*	*Q9*	***total***
Huckabee et al. 2003	Y	Y	NA	Y	Y	Y	NA	Y	Y	**7/9**
Nonaka et al. 2009	Y	Y	NA	Y	Y	Y	NA	Y	Y	**7/9**
Hiraoka 2004	Y	Y	NA	Y	Y	Y	NA	Y	Y	**7/9**
Cuellar et al. 2016	Y	Y	NA	Y	Y	Y	NA	Y	Y	**7/9**
Koganemaru et al, 2021	Y	Y	NA	Y	Y	Y	NA	Y	Y	**7/9**
Jestrovic et al. 2014	Y	Y	NA	Y	Y	Y	NA	Y	Y	**7/9**
Jestrovic et al. 2015	Y	Y	NA	Y	Y	Y	NA	Y	Y	**7/9**
Jestrovic et al. 2016	Y	Y	NA	Y	Y	Y	NA	Y	Y	**7/9**
Jestrovic et al. 2017	Y	Y	NA	Y	Y	Y	NA	Y	Y	**7/9**
Jestrovic et al. 2018	Y	Y	NA	Y	Y	Y	NA	Y	Y	**7/9**

Table 2. Characteristics of studies included in this review organized according to a modified PICO format.

Study	Population	Comparison		Recording devices	Outcomes
Huckabee et al., 2003	20 healthy, right-handed individuals, 10 males, 10 females, aged 18 - 35 years	Repetitive finger press movements	Repetitive dry swallows	EEG 45 surface electrodes, thermistor, EOG, SEMG, EAMM	Only early BP component was found for the volitional swallowing task, no laterality in swallow task, greater amplitude in finger tap and differences in polarity.
Nonaka et al., 2009	20 healthy right-handed subjects, 10 males and 10 females, mean age ± SD of 27.5 ± 1.9 years	Volitional dry swallowing task (MRCP)	Command dry swallowing task (CNV)	EEG 5 surface electrodes, EMG, EOC, nasolabial electrodes for GKP, nose sensor	Earlier onset of CNV with greater maximum amplitude and longer period than BP. EMG findings were identical in both conditions.
Hiraoka, 2004	7 healthy, right-handed subjects, aged 19-37 yrs	Volitional dry swallowing task	Volitional water swallowing task	EEG 3 surface electrodes, EMG	Larger early BP for the dry swallow, higher amplitude of positive potential for water swallows. No laterality found during swallowing.
Cuellar et al., 2016	25 healthy subjects, 24 right-handed and 1 ambidextrous, mean age 29 yrs	Repeated Swallowing task with water on visual cue	Repeated command tongue tapping on visual cue	EEG 68 surface electrodes, EOG, SEMG, 2 ECG electrodes on common carotid artery	Bilateral mu component in premotor and primary motor cortex, strong ERD during sEMG activity suggestive of cortical control during pharyngeal phase, evidence of sensorimotor control during esophageal phase, right-lateralized sensorimotor processing in pharyngeal and esophageal phases, stronger mu ERD for swallowing
Koganemaru et al., 2021	18 healthy volunteers, 17 right-handed and 1 left handed, 6 women and 12 men, mean age 34.2 ± 13.9 years	Volitional swallows 3s after a 3ml bolus of water was administered via tubing		EEG 32 surface electrodes, EMG submentally and in orbicularis oris, triple-axis accelerometer	ERD in frontal and parietal areas in beta band immediately before and maintained during activation with bilateral representation. Significant Corticomuscular coherence in frontal and parietal areas for theta, alpha and beta bands.
Jestrovic et al, 2014	55 healthy, aged 18-65 yrs	Five swallows with four different liquid viscosities (saliva, water, mildly thick liquid and moderately thick liquid)		EEG 64 surface electrodes, dual axis accelerometer sensor	Sex, liquid viscosity, and brain region significantly affected the EEG signals stationarity

Jestrovic et al., 2015	55 healthy, aged 18-65 yrs	five saliva swallows in the neutral head position	five saliva swallows in the chin-tuck head position	EEG 64 surface electrodes, dual axis accelerometer sensor	The brain network for swallowing in both head positions has small-world properties. It is different for the neutral head position compared with the brain network for the chin-tuck head position in some features
Jestrovic et al., 2016	55 healthy, aged 18-65 yrs, mean age 38.58	Five water, five nectar-thick & five honey-thick swallows in the neutral head position	Five water, five nectar-thick & five honey-thick swallows in the chin-tuck head position	EEG 64 surface electrodes, dual axis accelerometer sensor	Swallowing of various fluid viscosities has small world properties in both head positions and the brain network is different in the swallowing of various fluid viscosities, as well as between swallowing in the neutral and chin-tuck head positions
Jestrovic et al, 2017	55 healthy, aged 18-65 yrs	Five water, five nectar-thick & five honey-thick swallows in the neutral head position		EEG 64 surface electrodes, dual axis accelerometer sensor	Different brain networks between consecutive swallows and various viscosity fluids
Jestrovic et al, 2018	15 male healthy subjects, aged 18-35 yrs	Ten 1 ml water swallows, ten 5 ml water swallows and ten 10 ml water swallows	Ten 1 ml water swallows, ten 5 ml water swallows and ten 10 ml water swallows while watching a video	EEG 64 surface electrodes, dual axis accelerometer sensor	Differences in the brain networks between no-distraction swallowing and swallowing with distraction and in the swallowing of boluses of various volumes in all frequency bands of interest (i.e., Delta, Theta, Alpha, Beta, and Gamma)