

Original Article

Levels of brain wave activity (8–13 Hz) in persons with spinal cord injury

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Study design: Brain wave activity in people with spinal cord injury (SCI) was compared to brain wave activity in able-bodied controls.

Objectives: To investigate whether a spinal injury results in changes in levels of brain wave activity in the 8–13 Hz spectrum of the electroencephalography (EEG).

Setting: Sydney, Australia.

Methods: Monopolar, multichannel EEG assessment was completed for 20 persons with SCI and 20 able-bodied, sex- and age-matched controls. A total of 14 channels of EEG were measured across the entire scalp for all participants. Comparisons between the able-bodied and SCI participants were made across the frontal, central, parietal, occipital and temporal regions. Comparisons were also made for impairment level, that is, between participants with tetraplegia and paraplegia.

Results: Compared to the able-bodied controls, consistently reduced brain wave activity (measured by magnitude and peak amplitude) in the 8–13 Hz component of the EEG occurred in persons with SCI across all regions and sites, and differences were larger in the central, parietal and occipital sites. The SCI group also had consistently lower frequencies than the able-bodied controls. Furthermore, the subgroup of SCI participants with tetraplegia generally had significantly reduced brain activity (magnitude and peak amplitude) compared with the paraplegic subgroup and able-bodied controls.

Conclusions: The findings of this research enhance our understanding of changes in brain wave activity that could be associated with deafferentation that occurs following SCI, as well as provide essential data on the potential of SCI persons to use a ‘hands free’ environmental control system that is based upon 8–13 Hz brain activity.

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Keywords: spinal cord injury; deafferentation; alpha wave; 8–13 Hz activity

Introduction

The personal impact of spinal cord injury (SCI) in daily living is substantial.^{1–3} For example, persons with SCI have been shown to be at risk of negative life indicators such as high risks of drug use, hospitalisation, depression and anxiety.^{1–3} This strongly suggests the need for effective strategies that can help to lower such risks and raise quality of life. Suitable strategies could include psychological therapies,⁴ medical and pharmacological therapies⁵ as well as physical and occupational therapies. However, an alternative goal for enhancing the quality of life for persons with SCI is to reduce their level of dependency or conversely, by enhancing their independence. One strategy is to provide technology aids that enhance a person’s capacity to control devices in their immediate environment.^{6,7} Recently,

an environmental control system (ECS) that operates by detecting increases in electroencephalography (EEG) activity within the 8–13 Hz frequency range during eye closure has been trialled.^{8,9} EEG or brainwaves are electrical signals recorded from the scalp, produced by excitatory and inhibitory potentials of neurons. There are four well-established frequency bands in the EEG spectra, and the frequency band of 8–13 Hz has been referred to as the alpha rhythm when the signal has been recorded from the posterior regions of the brain. The accepted definition of the alpha rhythm is a rhythm at 8–13 Hz occurring during relaxed wakefulness over the posterior regions of the head, generally with higher voltage during eye closure.¹⁰

The efficacy of this EEG-based ‘hands free’ ECS was demonstrated with both able-bodied and 10 severely disabled people using conscious control of brain wave activity.^{8,9,11} All severely disabled participants were able

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to increase their 8–13 Hz activity when they closed their eyes and thus turn their television on and off, change channels and alter volume reliably and generally within 30 s, in their own homes.⁹ As the brain wave activity utilised in this ECS occurs within the 8–13 Hz frequency range, it is important to investigate whether brain activity in the 8–13 Hz range has altered following an SCI.

Since sensory afferent information to the brain is reduced in SCI, it would be expected that reorganisation in the cortex would occur and that this may influence the 8–13 Hz activity. It is known that the mammalian brain has a great capacity for adaptation and change.^{12,13} For instance, it has been shown in monkeys and other mammals that a loss of afferents from the skin is followed by reorganisation of the somatosensory cortex.¹⁴ While there are little data available in the literature with respect to the affect of SCI on EEG activity, differences in the motor potential between SCI and able-bodied controls have been found.¹⁵ The motor potential is a sharp peak in scalp potential preceding movement onset and maximum around movement onset. The study found a posterior relocation of the motor potential associated with finger and toe movements after SCI.¹⁵ Preliminary research on the impact of SCI on the alpha rhythm¹⁶ examined data from 17 SCI and 17 able-bodied subjects, but was limited to the acquisition of EEG data from only two occipital sites. Results from this study showed differences in alpha wave frequency and amplitude levels between the groups. SCI subjects had lower ‘eyes closed’ frequencies and reduced peak amplitudes compared to the able-bodied subjects in the O1 and O2 cortical sites.¹⁶ The aim of the present study, therefore, was to conduct a more thorough investigation over the whole scalp into the association between the 8–13 Hz EEG activity and SCI, in an additional group of SCI and able-bodied subjects.

Methods

Participants

Two groups participated in this research, including 20 subjects with SCI and 20 able-bodied subjects. The controls were individually matched to the SCI group for age and sex. The SCI group consisted of 18 males and two females, with a mean age of 34.3 years (SD = 10.6 years), 17 of whom had been injured in the past 12 months, while three subjects sustained their injury around 10 years prior to the study. The able-bodied group consisted of 18 males and two females, with a mean age of 33.7 years (SD = 11.2 years). Participants with SCI were approached for their willingness to participate in the study and their informed consent was obtained when they were patients in a rehabilitation ward. Eight of the persons with SCI had tetraplegia (all C5–C7 levels according to ASIA classification) and the remaining 12 had paraplegia (T4–T12 levels). All patients with SCI had clinically complete lesions (ASIA Impairment Scale class A). The able-bodied subjects

were selected from hospital and university staff. All able-bodied participants were matched to the SCI group on a case-by-case basis for sex and age (± 5 years). This study was approved by the institutions research ethics committee and participants were recruited into the study only after informed consent was obtained. Exclusion criteria for entry included a history of traumatic brain injury and non-English speaking.

EEG procedure

Data were recorded from 52 electrodes with an ActiveOne data acquisition system from Biosemi (www.biosemi.com). However, only 14 channels were used in the study reported in this paper. The channels corresponded to sites from the International 10–20 electrode system¹⁷ (Fp1, Fp2, F3, F4, Fz, C3, C4, P3, P4, T5, T6, Pz, O1 and O2). All channels were referenced to Cz.^{18,19} Skin preparation was performed on each electrode site to reduce the impedance below 10 k Ω . Signals were filtered to a bandwidth of DC 500 Hz, and sampled at 2048 Hz.

In-house software was written in Labview (version 6.1, National Instruments) to prompt the subject automatically (to open or close their eyes) and record EEG data. Subjects were instructed to follow audio prompts from the computer speaker. The program initially recorded 5 s of preliminary data (later discarded), which then audio prompted the subject to ‘close your eyes’ and ‘open your eyes’, alternating at 20-s intervals. Subjects were asked to keep their gaze toward the computer screen when their eyes were open. Three intervals each of eyes-closed and eyes-open data were collected and saved to the disk. The EEG data record was marked at the beginning of each audio prompt to aid postanalysis.

Postprocessing software, written in Labview, selected data from the three eyes-closed intervals, as this is where the increased 8–13 Hz occurs. As only eyes-closed data are used, the first 2 s of each eyes-closed interval were discarded to ensure that data corresponded to an eyes-closed state. The remaining 18 s of each interval were subdivided into 2-s epochs, which were multiplied by a 4-term Blackman–Harris window, and transformed with an FFT to calculate the magnitude spectrum. Magnitude was calculated as the sum of the components in the FFT for the corresponding frequency range, and was averaged over all epochs in a trial, and further averaged over the three trials. Peak 8–13 Hz amplitude was calculated as the maximum FFT component among all epochs in a trial, and averaged over all trials. The peak 8–13 Hz frequency was also calculated as the frequency where peak amplitude occurred and averaged over all trials.

Statistical analysis

As data were normally distributed, the differences in the 8–13 Hz magnitude, peak amplitude and frequency of 8–13 Hz levels between groups were tested using

analysis of variance (ANOVA). Testing for differences between the tetraplegic and paraplegic subgroups was conducted using the Mann–Whitney *U*-test due to the lower numbers involved (as normality cannot be expected). Owing to the large number of ANOVAs needed to be performed between the two groups and between the SCI subgroups, the type I error rate was potentially high (that is, the risk of finding a false difference between groups). In addition, the relatively low numbers of subjects involved in the study also raised the possibility of a type II error (that is, the risk of not finding a true difference between the groups). Therefore, in addition to regular hypothesis testing, a method called the sign test was used in order to indicate the consistency of the direction of difference between groups rather than just base a decision on the size of the difference. The sign test was used to determine the probability that the SCI group would always be lower than the EEG values of the able-bodied group. A value of 0.5 was therefore given to each prediction of difference for all 14 sites between the two groups, since there is theoretically a 1 in 2 probability of the SCI group being greater or lower than the able-bodied group EEG values. A value of 1 would be given to each incorrect prediction (that is, the SCI EEG value was actually greater than or equal to the able-bodied group). Using this technique, the probability of finding valid differences in a specified direction in the 14 sites can be estimated.

Results

8–13 Hz magnitude differences

Table 1 shows the 8–13 Hz magnitude values for both the SCI and able-bodied groups. Based upon the size of difference, only the T6 and O2 sites reached significance at the $P < 0.05$ level. However, the SCI group had

consistently lower magnitude values in all 14 sites. These differences become greater in posterior sites. The sign test suggests that the probability of all 14 able-bodied sites having greater magnitudes by chance is almost 1 in 17,000 (that is, $(0.5)^{14} = 0.00006$).

8–13 Hz peak amplitude differences

Table 2 shows the 8–13 Hz peak amplitude values associated with the increase in the EEG with eyes closed for both the SCI and able-bodied groups. Larger differences were found between the two groups in 8–13 Hz wave peak amplitudes in posterior and central sites, although a significant difference ($P < 0.05$) was only found in the O2 site. However, there were consistently reduced peak amplitudes found in the SCI group in all 14 sites compared to the able-bodied group. Again, the sign test suggests the probability of all 14 sites having lower SCI values by chance is 1 in almost 17,000.

8–13 Hz synchronisation frequency differences

Table 3 shows the 8–13 Hz peak frequency values for both the SCI and able-bodied groups. There were greater differences found between the two groups in 8–13 Hz wave peak frequencies in the posterior and central sites. Significant differences ($P < 0.05$) between the two groups were found in O1, O2, T6, P3, P4 and PZ sites. However, there were consistently reduced frequencies found in the SCI group in 13 of the 14 sites. Again, the probability of this happening by chance is 1 in almost 10,000 (that is, $(0.5)^{13} = 0.0001$).

Paraplegic and tetraplegic subgroups differences

Significant differences were found between the paraplegic and tetraplegic subgroups and the controls.

Table 1 Statistics for 8–13 Hz magnitude (μV) of SCI and the able-bodied groups, including results of the sign test prediction as well as *F* values and significance

Site	Mean	SCI SD \pm 95% CI	Mean	Able-bodied SD \pm 95% CI	Difference SCI < control	<i>F</i>
FP1	14.4	4.3 \pm 2.0	18.5	9.8 \pm 4.6	Yes	2.9
FP2	14.2	4.2 \pm 2.0	18.4	9.9 \pm 4.7	Yes	3.1
F3	10.9	3.9 \pm 1.7	14.5	8.3 \pm 3.9	Yes	3.0
FZ	10.1	3.8 \pm 1.7	13.3	8.6 \pm 4.1	Yes	2.2
F4	10.8	3.7 \pm 1.7	14.2	8.2 \pm 3.9	Yes	2.8
C3	10.2	4.4 \pm 2.0	13.3	7.2 \pm 3.4	Yes	2.5
C4	9.9	4.7 \pm 2.1	13.3	8.2 \pm 3.8	Yes	2.5
T5	24.2	10.7 \pm 5.0	30.7	16.8 \pm 7.9	Yes	2.1
P3	20.2	10.4 \pm 4.9	22.3	13.1 \pm 6.1	Yes	0.3
PZ	14.4	8.2 \pm 3.8	19.5	11.5 \pm 5.3	Yes	2.6
P4	19.2	9.9 \pm 4.7	26.5	15.7 \pm 7.4	Yes	3.1
T6	23.9	10.4 \pm 4.8	33.8	18.3 \pm 8.6	Yes	4.4*
O1	28.3	13.8 \pm 6.5	39.1	21.1 \pm 10.0	Yes	3.6
O2	27.7	12.9 \pm 6.1	41.4	21.7 \pm 10.2	Yes	5.9*

* $P < 0.05$

Table 2 Statistics for 8–13 Hz peak amplitude (μV) of SCI and the able-bodied groups, including results of the sign test prediction as well as F values and significance

Site	Mean	SCI		Mean	Able-bodied		Difference SCI < control	F
		SD	95% CI		SD	95% CI		
FP1	5.0	2.1	±1.0	6.4	3.8	±1.8	Yes	2.0
FP2	4.9	2.1	±1.0	6.4	3.7	±1.8	Yes	2.2
F3	3.8	1.7	±0.8	5.1	3.1	±1.5	Yes	2.7
FZ	3.7	1.7	±0.8	4.8	3.0	±1.8	Yes	2.1
F4	3.9	1.7	±0.8	4.9	2.8	±1.3	Yes	1.9
C3	3.3	1.7	±0.8	4.3	2.1	±1.0	Yes	2.7
C4	3.3	1.8	±0.9	4.3	2.9	±1.4	Yes	1.8
T5	8.7	4.5	±2.1	11.2	6.9	±3.2	Yes	2.0
P3	7.3	4.1	±2.0	8.4	5.6	±2.6	Yes	0.5
PZ	5.5	3.5	±1.6	7.7	4.8	±2.3	Yes	2.6
P4	6.9	3.9	±3.8	9.8	6.1	±2.8	Yes	3.2
T6	8.7	4.4	±2.0	12.2	6.9	±3.2	Yes	3.6
O1	10.3	5.8	±2.7	14.9	8.6	±4.0	Yes	3.9
O2	10.2	5.8	±2.7	15.6	8.6	±4.0	Yes	5.4*

* $P < 0.05$ **Table 3** Statistics for 8–13 Hz synchronisation frequency (Hz) of SCI and the able-bodied groups, including results of the sign test prediction as well as F values and significance

Site	Mean	SCI		Mean	Able-bodied		Difference SCI < control	F
		SD	95% CI		SD	95% CI		
FP1	9.2	0.9	±0.4	9.3	0.9	±0.6	Yes	0.2
FP2	9.4	1.0	±0.5	9.5	1.0	±0.5	Yes	0.1
F3	9.5	1.0	±0.5	9.4	0.9	±0.4	No	0.0
FZ	9.2	1.0	±0.4	9.5	1.1	±0.5	Yes	0.9
F4	9.3	0.9	±0.4	9.5	0.9	±0.5	Yes	0.8
C3	9.3	1.0	±0.5	9.7	1.0	±0.5	Yes	1.5
C4	9.4	1.1	±0.5	9.8	1.0	±0.5	Yes	1.6
T5	9.3	0.9	±0.5	9.8	0.8	±0.4	Yes	2.4
P3	9.4	1.0	±0.4	10.1	1.0	±0.5	Yes	4.5*
PZ	9.4	1.0	±0.5	10.1	1.1	±0.5	Yes	4.1*
P4	9.4	1.0	±0.4	10.1	1.0	±0.5	Yes	4.2*
T6	9.3	0.9	±0.4	10.0	0.9	±0.4	Yes	5.5*
O1	9.4	0.9	±0.4	10.1	0.8	±0.4	Yes	5.6*
O2	9.5	0.8	±0.4	10.2	0.8	±0.3	Yes	8.4**

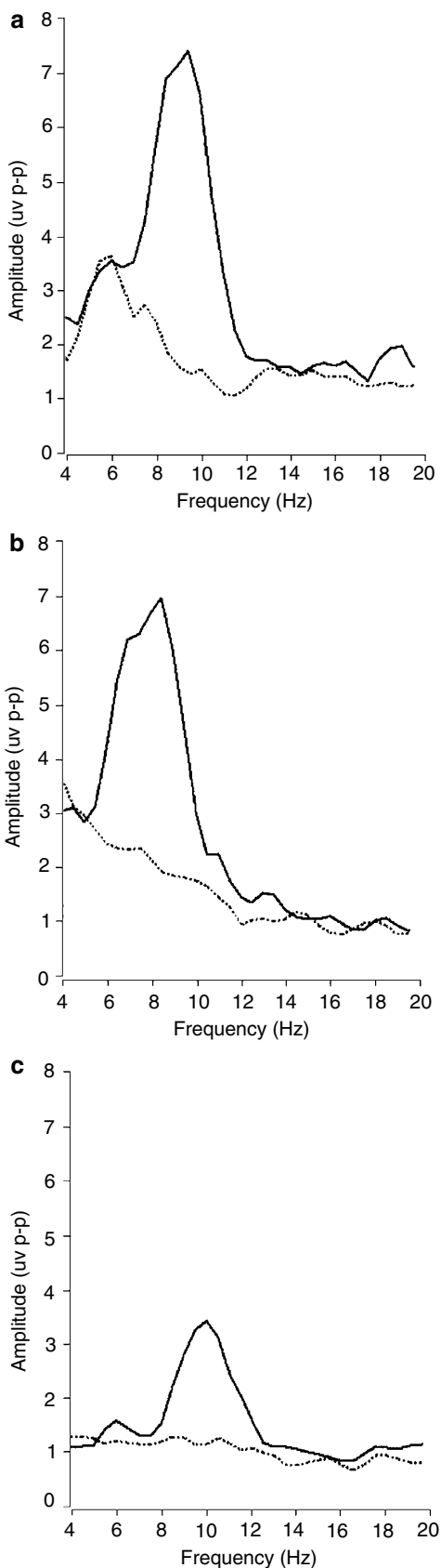
* $P < 0.05$, ** $P < 0.01$

Furthermore, while no significant differences were found between the paraplegic subgroup and the able-bodied controls, differences were still in the predicted direction. Figure 1 shows a comparison of eyes-closed and eyes-open 8–13 Hz magnitudes (μV) in the three groups across the occipital site O1. Table 4 shows the 8–13 Hz magnitude, peak amplitude and frequency of the tetraplegic group. As suggested by the results of the sign test, the tetraplegic group were consistently lower than those of the able-bodied group in terms of 8–13 Hz magnitude (sign test $P = 0.00006$), peak amplitude (sign test $P = 0.00006$) and frequency (sign test $P = 0.0001$). Many of these differences reached statistical significance ($P < 0.05$) especially in the posterior, central and temporal sites (see Table 4). The tetraplegic group also had consistently and significantly lower EEG

magnitudes and peak amplitudes than the paraplegic subgroup. However, there were no significant differences in frequency between the SCI subgroups.

Discussion

The aim of this research was to investigate the influence of SCI on the 8–13 Hz EEG activity. It was believed important to examine the EEG activity in the SCI group for two reasons: (i) little is known about the EEG results of reduced sensory input in this population and (ii) the information will help improve the utility of a 'hands-free' ECS for the severely disabled based upon conscious control of 8–13 Hz activity. The ECS has been designed to help alleviate some of the independence challenges



associated with severe disability such as maybe found in SCI.

The results of the paper were similar to those found in the preliminary study¹⁶ as there were significant differences found between the SCI group and able-bodied group in terms of the 8–13 Hz magnitude, peak amplitude and frequency in the posterior sites. When the SCI group was broken down further into subgroups (paraplegia and tetraplegia), significant reductions in brain activity were found in the central, temporal and posterior cortical sites in the tetraplegic subgroup. There were no significant differences found between the able-bodied group and the subgroup with paraplegia, suggesting that the reduction in sensory input was not as great as in the subgroup with tetraplegia. There were no significant differences in the frontal regions between any of the groups. The lack of significant differences may reflect the sample power in this study. If say, the number of participants was doubled, then significant differences between the SCI group and able-bodied group would have substantially increased.

It is important to note that the direction of difference over all 14 sites was almost always showing that SCI EEG values were lower than those of the able-bodied group. This suggests that deafferentation may be associated with reduced 8–13 Hz activity all over the cortex. Further research is now needed to determine whether the reduced sensory input that occurs following an SCI (especially in tetraplegia) directly results in reduced brain wave activity in the 8–13 Hz spectrum. It is important to note that the reduction of EEG activity was not limited to the 8–13 Hz spectrum. In order to determine whether the changes in EEG activity were limited to the 8–13 Hz spectrum, we studied changes in the EEG from 3 to 50 Hz and found consistently lower EEG activity in the SCI group. This reduction in brain wave activity found in the SCI group suggests that an overall reduction in EEG activity may be associated with an overall reduction of sensory input. Notwithstanding the above, decreased 8–13 Hz activity (traditionally referred to as alpha blocking in the posterior regions) is known to be an indicator of increased neural processing.²⁰ However, the EEG reductions seen across the 3–50 Hz spectrum in this study may not be consistent with this interpretation. Furthermore, these reductions in brain wave activity are unlikely to be the result of drugs commonly administered during rehabilitation such as antispasmodics (eg baclofen) and antidepressants. In the current group of participants, there were four patients taking baclofen and six taking gabapentin for neuropathic pain, with four of those also taking low-dose tricyclic antidepressants. It has been shown^{21–24}

Figure 1 Comparison of eyes-closed (solid line) and eyes-open (dotted line) 8–13 Hz magnitude (μV) between the able-bodied (a), SCI paraplegic (b) and SCI tetraplegic subgroup (c) in three aged-matched representative samples at electrode site O1

Table 4 Statistics for 8–13 Hz values for the tetraplegic subgroup of the SCI subjects, including *F* values and significance of comparisons to the able-bodied group

Site	Magnitude		<i>F</i>	Peak amplitude		<i>F</i>	Frequency		<i>F</i>
	Mean	<i>SD</i>		Mean	<i>SD</i>		Mean	<i>SD</i>	
FP1	13.4	3.8	2.0	4.4	1.4	2.1	9.1	0.9	0.2
FP2	13.0	3.1	2.2	4.3	1.3	2.4	9.4	1.1	0.0
F3	9.3	3.1	2.9	3.1	1.2	3.0	9.5	1.1	0.1
FZ	8.6	3.2	2.2	3.0	1.3	2.7	8.8	0.7	2.9
F4	9.3	2.8	2.6	3.1	1.0	3.0	9.2	0.6	0.5
C3	6.9	2.1	5.8*	2.2	0.9	7.4*	9.5	1.0	0.2
C4	7.0	1.9	4.5*	2.3	0.8	3.4	9.2	0.8	2.1
T5	17.2	7.3	4.7*	5.9	2.8	4.5*	9.4	0.9	1.2
P3	13.2	5.6	3.6	4.4	2.1	3.9	9.4	0.7	3.3
PZ	9.7	4.6	5.4*	3.3	1.6	6.1*	9.1	0.6	5.5*
P4	12.9	5.5	5.6*	4.5	1.7	5.7*	9.2	0.8	4.7*
T6	17.9	5.8	5.7*	6.4	2.8	5.1*	9.1	0.6	6.0*
O1	18.7	6.6	7.1*	6.5	2.8	7.2*	9.3	0.5	6.9*
O2	19.8	6.8	7.5*	7.1	3.4	7.3*	9.3	0.5	9.6*

* $P < 0.05$, ** $P < 0.01$

that these drugs are more likely to increase 8–13 Hz activity rather than reduce it.

Despite there being a less 8–13 Hz peak amplitude and magnitude brain activity in participants with SCI compared to able-bodied participants (especially in the tetraplegic subgroup), the levels of brain activity found in the SCI group were still substantial enough to use the hands-free ECS. Also, the small reductions in frequency associated with eyes closed in the SCI group would not challenge the utility of using the ECS, as the system can be tuned over a wide frequency range when waiting for an increase in 8–13 Hz activity. However, the reduced size of the 8–13 Hz EEG values found in the subgroup with tetraplegia in comparison to the paraplegia group, suggests that a minority may have difficulty using the ECS. This difficulty would be increased if a user produced frequent muscle spasms. Possible solutions include administering baclofen (which is also known to increase the 8–13 Hz activity) and improving the artefact control in the ECS.¹¹ In conclusion, the findings of this research enhance our understanding of changes in brain wave activity as a result of deafferentation that occurs following SCI. Also, it provides essential data on the potential of persons with SCI to use a 'hands-free' ECS that is based upon the 8–13 Hz brain activity. The findings of this study should therefore improve the development of the hands-free ECS technology¹¹ as well as increase our understanding of the method used to detect the 8–13 Hz waves in severely disabled users.

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