Semantic and BCI-performance in completely paralyzed patients: Possibility of language attrition in completely locked in syndrome

Majid Khalili Ardali^{a,b}, Aygul Rana^a, Mehdi Pourmohammad^b, Niels Birbaumer^{a,c},
Ujwal Chaudhary^{a,c,*}

^a Institute of Medical Psychology and Behavioral Neurobiology, University of Tübingen, Tübingen, Germany

^b Department of Cognitive Linguistics, Institute for Cognitive Science Studies (ICSS), Tehran, Iran

^c Wyss Center for Bio and Neuroengineering, Geneva, Switzerland

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ABSTRACT

Patients with completely locked-in syndrome (CLIS) are incapable of any voluntary muscle movement and do not have any means of communication. Recently functional near infrared spectroscopy (fNIRS) based brain computer interface (BCI) has been successfully used to enable communication with these patients. The developed fNIRS-BCI system relies on the intactness of language comprehension in these patients in all dimensions of language. Interwoven language and motor cortex in brain, and lack of muscular activity in long run, can cause language attrition due to complete immobility in CLIS patients. In this study we have investigated effects of semantic content of sentences presented to a CLIS patient on the performance of the BCI system during a YES/NO paradigm. Comparison of communication success rate in BCI classification between different semantic categories indicate that semantic content of sentences presented to a CLIS patient can affect the BCI performance. Affected concepts are mostly associated with executive words. These findings can be beneficial towards development of more reliable communication device for patients in CLIS. In addition, these results may assist in elucidating the cognitive changes in completely paralyzed patients with the passage of time since the onset of total immobility.

1. Introduction

“Sight and hearing were the only senses remaining, and they, like two solitary sparks, remained to animate the miserable body which seemed fit for nothing but the grave; it was only, however, by means of one of these senses that he could reveal the thoughts and feelings that still occupied his mind, and the look by which he gave expression to his inner life was like the distant gleam of a candle which a traveler sees by night across some desert place, and knows that a living being dwells beyond the silence and obscurity.”

This poetic definition of a locked-in patient was given by Alexander Dumas in his book *The Count of Monte Cristo*, long before the Locked-In Syndrome (LIS) was introduced in the scientific literature (Dumas & Sante, 2004). Later, Bauer et al defined LIS in which patient is completely immobile except for voluntarily eye movement or blinking (Bauer, Gerstenbrand, & Rumpl, 1979). Patients with neurodegenerative disease like motor neuron disease (MND), lose the voluntarily control of their muscles and transits to LIS as time passes. When the

patient loses the control of their eye movement, which is usually the last active muscle (Murguialday et al., 2011), the patient is in the completely locked-in state (CLIS) (Smith & Delargy, 2005). The patients in CLIS are then left without any means of communication. Ned Block, philosopher of mind, has argued that despite the lack of capabilities to self-report in patients in CLIS there is no magical reason to believe that the conscious state has disappeared (Block, 2007), but these arguments have always been challenged due to the unclear definition of the consciousness. “Consciousness” is an ill-defined umbrella-term and can cause ambiguity while shifting from one paradigm (e.g. philosophy of mind) to another (e.g. clinical psychology). To be precise, here we only used the term consciousness in order to refer to the subjective experience of self and the ability to voluntarily respond to environmental stimuli, which can be gained by processing external stimuli using sensory information and by modulating the brain response.

Empirical evidence has demonstrated that verbal comprehension in these patients are still present and patient can intentionally modulate thinking process in experimental tasks (Chaudhary, Xia, Silvoni, Cohen, & Birbaumer, 2017; Sellers, Ryan, & Hauser, 2014; Wilhelm, Jordan, &

* Corresponding author.

E-mail address: ujwal.chaudhary@uni-tuebingen.de (U. Chaudhary).

Birbaumer, 2006). In an interesting experiment, a CLIS patient was asked YES/NO questions and instructed to think of lemon or milk corresponding to YES and NO, respectively. Significant difference in level of salivary pH between this two conditions was reported (Wilhelm et al., 2006), which can be interpreted as proper comprehension of the conditioning task by patient. These findings led to an extensive research toward development of a BCI system to achieve a reliable communication with these patients. Different brain imaging techniques such as electroencephalography (EEG), functional near infrared spectroscopy (fNIRS) and functional magnetic resonance imaging (fMRI) and also the combination were used to achieve this goal (Chaudhary, Birbaumer, & Curado, 2015; Chaudhary, Birbaumer, & Ramos-Murguialday, 2016; Gibson et al., 2014; Hinterberger, Kübler, Kaiser, Neumann, & Birbaumer, 2003; Sellers et al., 2014). Brain implants using micro-electrodes were particularly successful in achieving BCI communication in paralyzed patients (Hochberg et al., 2006; Milekovic et al., 2018). Brain imaging is sometimes accompanied with other experimental features like electrical stimulation (De Massari et al., 2013) or classical conditioning (Ruf et al., 2013). The ideal system would be the one that can discriminate between two different mental states, so that it can be used as binary switch for a speller system. Even though different computational methods and psychological methodologies have been applied and considering impressive improvement of imaging techniques during recent years, a reliable voluntarily communication has not been established yet, and the best BCI communication performance reported so far is 70% in binary YES/NO questions paradigm (Chaudhary et al., 2017) and though that is more than chance level, it is not good enough to achieve reliable online communication. Still, BCI provides the only approach to end this silence and enable communication in patients in CLIS.

To achieve BCI based communication, experimenters usually present a sentence with known Yes or No answer (e.g. “Your name is Majid”) and instruct the patient to respond by performing particular thinking activity. This mental activities could be imagining of playing tennis and imagining to move around the room (Gibson et al., 2014) or simply thinking yes or no (Chaudhary et al., 2016, 2017; Gallegos-Ayala et al., 2014) or doing a mental calculation and resting. Different features are extracted from the source signal, and using machine learning algorithms a classifier is trained to classify two conditions and then the same model is being used to predict the outcome of open question answered, where the answer is not priori known for experimenter (e.g. Do you have pain in your back?).

In all the experimental paradigm mentioned above, intactness of linguistics abilities in all dimensions of the language is assumed while evidences indicate that neural networks involved in linguistic tasks, overlap with neural networks for movement and motor actions (Hadar, Wenkert-Olenik, Krauss, & Soroker, 1998; Iverson & Goldin-Meadow, 1998; Rizzolatti & Rozzi, 2016). ‘Action perception theory’ purports that during linguistic tasks, sensorimotor circuits become active (Pulvermüller, Moseley, Egorova, Shebani, & Boulenger, 2014; Rizzolatti & Rozzi, 2016) and lowers the threshold for post activations. For instance, when the healthy participants are reading aloud the functional links between hand motor area of the language dominant hemisphere and language processing areas in brain, lowers excitation threshold in transcranial magnetic stimulations (TMS) (Meister et al., 2003). Based on motor theory of speech, motor activation plays a critical role in speech perception (Liberman & Mattingly, 1985) and there is ample evidence to state that, language does not only require the activity of motor system but is deeply embedded in motor organization (Rizzolatti & Rozzi, 2016). Overlapping motor cortical area and language functioning networks (Binder et al., 1997; Hadar et al., 1998; Hickok & Small, n.d.; Huth, De Heer, Griffiths, Theunissen, & Gallant, 2016) are not only effective in the process of language production but also in the process of perceiving any speech signal (Pulvermüller, 1999). During perception of the semantic content of a word, cortical motor area is activated even if the participant is not actively attending

to the language input. Importantly, this brain activation is not post comprehension thought process but is involved in the semantic comprehension process (Moseley & Pulvermüller, 2018).

Neural substrates for thought, language and movement are intrinsically interwoven and functionally interdependent (Moseley & Pulvermüller, 2018). Cognition is the product of reactivation of the neural basis acquired during initial learning process in sensorimotor network (Barsalou, 2008; Gallese & Lakoff, 2005; Moseley & Pulvermüller, 2018; Thompson, 2014). During acquisition of new words, depending on the semantic content of that word, a particular combination of neural basis are activated in the sensorimotor network, and while retrieving that word, most of that network is activated (Pulvermüller, 1999) and as a result during the perception of different semantic content, activation in different neural pathways are required (Binder, Westbury, McKiernan, Possing, & Medler, 2005). In the most rigorous perspective, sensorimotor approach implies that LIS patient’s perception should be severely deficient since they are unable to move and proprioceptive afferents are absent (Kyselo & Di Paolo, 2015) but empirical finding demonstrates absence of extensive cognitive deficits in these patients (Schnakers et al., 2008). However, as different concepts are acquired by different mechanisms, it is very unlikely that perception and ability to comprehend various concepts are uniformly preserved after the onset of total immobility and changes in neural activation thresholds. In this study we have investigated effects of linguistic features on the success rate in a BCI system during communication with CLIS patients. In accordance with a Hebbian associative theory of language formalized by Pulvermüller et al. (1994) following a model articulated first by Braitenberg (1996), we hypothesize that, “non-use” of motor semantic networks in complete paralysis and lack of appropriate proprioceptive input from relevant muscle groups, the excitation threshold for semantic nodes for action words and action phrases is increased in CLIS, hence performance of the BCI to questions containing action words in comparison to object words is decreased.

2. Methods

The data for this report was acquired by Chaudhary et al., 2017, during the BCI study with four different patients in CLIS. During each session, patients were presented 10 questions with “Yes” answer and 10 questions with “No” answer, randomly. Meanwhile, BCI system using fNIRS signal and support vector machine (SVM) classifier detected Yes or No answers and gave feedback to patient. For more details on the BCI study see Chaudhary et al. (2017). Here we analyzed results from 11 feedback sessions performed by Patient B (61 Old, male) reported in the same publication. For the other 3 patients reported in Chaudhary et al. (2017) the analysis reported in this paper could not be carried out because of the continuous update of the sentence database.

For patient B, in total, 174 different sentences were presented for 218 times. Each sentence was presented to the patient at least once. The sentences were constructed by the experimenter based on the information obtained from patient’s family and were recorded by a family member of the patient. The sentences were typically about the patient himself (e.g. Do you have brown hair?), the biography of the patient (e.g. You have two daughters, or You have been to China.) or general knowledge information (e.g. Berlin is the capital of Germany).

Sentences presented were categorized based on their linguistic features. Six different categories were applied and each category consisted of two opposite attributes. Each sentence comprised of attribute in each category. For instance, in the first category, two attributes are “Question” and “Statement” and each sentence belongs only to one of them. Finally, performance of BCI was defined as the ratio of correct answer detected by the BCI system for each attribute to total questions presented to the patient in the same category.

2.1. Linguistics features

Category 1: Statement versus Questions - Based on the syntactical structure of each sentence, sentences were categorized in statements and questions. For instance, “Your name is Majid” categorized as statement and “Is your name Majid?” categorized as question.

Category 2: Frequent versus Occasional - Word frequency is an indicator of how frequent a particular word is used in general discourses in a particular language. “German dictionary of word frequencies, Leipzig Corpora Collection” (Goldhahn, Eckart, & Quasthoff, 2012) was used to calculate frequency of the words. For each sentence, the frequency index was defined as the summation of word frequencies in that sentence divided by the total number of words in the sentence (Eq. (1)). Sentences with frequency index higher than the mean of frequency indexes were ranked as Frequent and the rest as Occasional.

$$\text{FrequencyIndex} = \frac{\sum_{\text{word}}^{\text{sentence}} \text{frequency of word}}{\text{Number of words in sentence}} \quad (1)$$

Category 3: Emotional versus Non-Emotional - A sentence can carry positive, negative or neutral emotional content, which can regulate neural pathway of perceiving and analyzing that sentence in brain (Vuilleumier, 2005). In this study, dictionary of sentiment, Germanlex which comes from PolArt (Klenner, Fahrni, & Petrakis, 2009) and was used at Polcla¹ project (Wiegand, Wolf, & Ruppenhofer, 2017) was used. It contains information about the sentiment that each word expresses, the polarity of that sentiment (positive, negative or neutral) as well as intensity of sentiment which is a value between -1 and 1 (Klenner et al., 2009). We defined emotional index of a sentence as sum of positive and negative values minus neutral value of all the words in that sentence (Eq. (2)). Sentences with emotional index more than 0.5 were ranked as emotional and the rest as non-emotional sentences.

$$\text{EmotionalIndex} = \sum_{\text{word}}^{\text{sentence}} |NEG| + |POS| - |NEU| \quad (2)$$

Category 4: Abstract versus Concrete - It has been demonstrated that there are distinct brain systems for processing abstract and concrete words and there are disparate neural networks for processing them (Binder et al., 2005; Pulvermüller, 2013; Scorolli et al., 2011; Wiemer-Hastings, Krug, Xu, & Com, 2001). In this study, we borrowed the definition by Scorolli et al and ranked the nouns and verbs. Nouns that refer to graspable objects were ranked as concrete and nouns that do not refer to any manipulable objects were ranked as abstract words. Verbs that refer to hand actions were ranked as concrete and verbs that do not refer to any motor actions were ranked as abstract (Scorolli et al., 2011). Then sentences containing abstract noun and abstract verbs were ranked as abstract and sentences with concrete verbs and concrete nouns ranked as concrete. Sentences with the combination of concrete and abstract verb and nouns were excluded from the analysis in this category. For instance, “Did you break the vase?” was ranked as concrete and “Sky is blue” was ranked as abstract.

Category 5: Motion versus Motionless - Using the concept of action, words which only refer to movements of the one's body (Pulvermüller, 1999), motion words are defined as words with executive affordance representing any kind of motion or movements, sentences including these words were ranked as motion otherwise as motionless. For instance, “Airplanes move faster than trains” was ranked as Motion and “Do you wear glasses?” was ranked as Motionless.

Category 6: Self-Related versus Not Self-Related - If a sentence represents any type of information about the patient identity it was ranked as self-related otherwise as not self-related, for instance “You have brown hair” was ranked as Self-Related and “Birds can fly” was ranked as Not Self-Related.

2.2. Analysis

Each sentence presented to the patient was labeled and categorized based on the linguistic features defined above and BCI performance was calculated. The BCI performance was defined as the percentage of correctly classified answer of the presented sentence in a category. For each category, performance of the BCI was compared between two attributes in the same category. e.g. in the first category, performance of BCI system was compared between questions and statements and so on for different categories as defined above. For comparison chi-square statistics was used. Chi-square was calculated using online free statistical calculator for comparison of proportion, provided by MEDCALC (“MedCalc Software bvba, Ostend, Belgium;”, 2016). In addition to the comparison of single features, sentences with two different linguistic features were compared. e.g., among the sentence with frequent words, performance of the BCI was compared between emotional and non-emotional sentences. Categories with less than 10 sentences were excluded from analysis.

3. Results

For each complimentary pair of features Table 1 shows the total number of sentences in each group, BCI performance for each feature, chi-square and level of significance for difference between two categories. Results indicate that there is no significant difference in the BCI performance between two attributes in one category, although in category 1 there is a near significant ($p = 0.06$) difference in the performance of the BCI with better performance in statements in compare to questions.

Imbalanced distribution of linguistics features among the sentences makes it impossible to compare all possible combination for paired attributes and categories with less than 10 sentences were eliminated from analysis. Table 2 shows the categories for which the BCI performance was significantly ($p < 0.05$) different between two attributes. There was significant difference ($p = 0.001$) in BCI performance in sentences with abstract content versus concrete ones, when the sentence represented to the patient has motion contents. The second group of features for which the BCI performance was significantly different ($p = 0.02$), was when the sentence presented was about the patient himself (i.e. self-related). Among all the self-related sentences, there was clear difference in the BCI performance in motion sentences versus motionless ones. For other combination of linguistics attributes there was no significant results.

4. Discussion

The difference between BCI performance in two groups of sentences with different linguistic features suggest that semantic information of sentences presented to a CLIS patients plays an important role in control of BCI. It is evident that neural process of motor related networks plays a significant role in the processing of sentences by the CLIS patient, because only with inclusion of motor related words significant differences emerged. The “preference” of motionless self-related sentences could reflect the transfer of motor paralysis state of the patient's body into the cognitive imagery domain. Associative connections between motionless contents related to one's own body are strengthened in CLIS because associative pairings with body-motions extinguishes. We predicted this results (Birbaumer, 2006; Kübler & Birbaumer, 2008) and speculated (Chaudhary et al., submitted) that sufficient quality of life rating in chronic paralysis could be a consequence of extinction of voluntary, goal directed thinking due to the absence of contingent “fulfilment” of expectancies and consequences in a motionless, non-communicative state such as CLIS. Frustrative non-reward, one of the most frequent causes of human stress becomes highly unlikely with the lack of contingent expectancies probably contributing to the sufficient quality of life in LIS (Linse et al., 2017).

¹ A Polarity Classifier Incorporating Polarity Shifting for German.

Table 1

Comparison of BCI performance in different linguistic categories with two attributes for each category. Chi-square and p-Value indicates difference of BCI performance between two attributes. Performance are presented in percentage.

Feature	Number of Questions	Performance	Chi-Square	p-Value
Abstract/Concrete	142/49	47.2/55.1	0.905	0.34
Frequent/Occasional	82/136	51.2/46.3	0.490	0.48
Question/Statement	99/119	41.4/53.8	3.313	0.06
Motion/Motionless	73/145	43.8/50.3	0.818	0.36
Emotional/Non-Emotional	28/190	50/47.9	0.043	0.83
Self-Related/Not Self-Related	92 / 126	42.4/52.4	2.12	0.14

Table 2

Comparison of BCI performance in different linguistic categories with two attributes for each sentence. Chi-square and p-Value indicates difference of BCI performance between two attributes. Performance are presented in percentage. Results with p-Value > 0.05 are not presented.

Feature	Number of Questions	Performance	Chi-Square	p-Value
Motion – Abstract/Motion – Concrete	28/39	25/56.9	6.646	0.001
Self-Related – Motion/Self-Related – Motionless	48/44	31.3/54.5	5.004	0.02

The Hebbian “rules” of learning state that coactivation of neurons determines association of cells and leads to the development of functional units called cell assemblies (Hebb, 1967). Electrophysiological studies demonstrate that frequent activation of cell assemblies, strengthens the synaptic connection between these two cells. More importantly, activation of presynaptic neuron without the activation of post synaptic neuron leads to the weakening of their synaptic connection (Artola, Bröcher, & Singer, 1990). For action words (words that refer to body movements), perisylvian assembly representing the word form would become linked to neurons in motor, premotor and prefrontal cortices related to motor programs (Hauk, Johnsrude, & Pulvermüller, 2004; Pulvermüller, 1999). Hence, extensive reduction in activation of motor cortex neurons after the onset of CLIS in patient's brain can increase the activation threshold in perisylvian assembly, as a results while recalling concepts that requires activation of this network more input trigger is need to activate the conceptual motor related nodes, otherwise it can reduce the “ability” of perceiving and comprehending executive words. Thereby sentences with action words presented to a CLIS patient might appear ambiguous to them. It could be one of the reasons why no reliable communication with these patients have been achieved yet (Kübler & Birbaumer, 2008).

Neural basis for comprehension and production of words in different semantic domains are structurally different and different pattern of neural activity are generated during the processing of words in different semantic domains. For instance, concrete words are expected to be stored in the brain contralateral while abstract words are more ipsilateral, therefore process of words in these two categories require different neural pathways (Binder et al., 2005; Pulvermüller, 1999; Scorolli et al., 2011). Considering these linguistics fractures while training a classifier might help to discriminate different pattern of signal and increase classification accuracies.

5. Conclusion

Investigation on the effects of semantic content of sentence presented to a CLIS patients shows clear discrimination in BCI performance among different semantic domains. This could suggest changes in language comprehension and production in CLIS after the onset of total immobility and difficulties in perception and/or production of words in executive concepts highly related to the patient's body. Our findings also suggest that the semantic aspects of sentences used in such tasks must be considered in future BCI communication experiments. In the

present study, imbalance of syntactical features distribution among all the sentences, made it impossible to analyses effects of syntactic aspects of a sentence presented to the patient on BCI performance, but in our future research we intend to include syntactic analysis too. On the basis of the promising findings presented in this paper, work on the remaining issues is continuing and will be presented in future papers.

Statement of significance

In the current manuscript we investigated the reorganizational changes in language comprehension by a patient with complete paralysis. We elucidate the importance of intactness of motor system for processing the semantic meaning of language; where in a patient in CLIS process self-related and motion contents, better than self-related

and motionless contents.

Declaration of Competing Interest

The authors declared that there is no conflict of interest.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.bandl.2019.05.004>.

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