Tactile Pressure Brain-computer Interface Using Point Matrix Pattern Paradigm

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***Abstract*—The paper presents a tactile pressure stimulus-based brain-computer interface (BCI) paradigm. 3×3 pressure pins matrix stimulus patterns are presented to the subjects in an oddball paradigm allowing for "aha-responses" generation to attended targets. A research hypothesis is confirmed with the results with five subjects performing online BCI experiments. One of the users could score with 100% accuracy in online ten averages based BCI test. Three users scored above chance levels, while one remained on the chance level border. The presented pilot study experiments and EEG results confirm the effectiveness of the proposed tactile pressure stimulus based BCI.**

Keywords*—BCI; tactile BCI; P300; EEG; brain signal processing;

I. Introduction

A brain–computer interface (BCI) is a technology that uses neurophysiological signals (brainwaves) of paralyzed or locked–in patients to allow communication with others or a control of external devices without depending on any muscle activity [1]. The BCI technology has contributed already to patients' life improvement who suffer from severe paralysis due to diseases like an amyotrophic lateral sclerosis (ALS) [1]. The majority of BCI applications is based on a visual modality, which generates the most reliable event related potentials (ERP) so far [2]. However, ALS patients in the advanced stages sometimes lose their ability to control intentionally even their eye gazes [3], and therefore they need other types of BCI for communication.

Alternative solutions have been proposed recently to make use of spatial auditory [2] or tactile modalities [3], [4]. Meanwhile, the tactile BCI seems to offer the better communication options in comparison with visual and auditory modalities in case of locked–in–syndrome (LIS) patients [5]. The paradigm proposed in this paper is a BCI using tactile pressure stimulus generated by solenoids, which we refer to in brief as tactile pressure BCI (tpBCI). The tpBCI device can have various stimuli patterns generated and body area stimulated, and therefore it could be adopted to various patient symptoms. The presented approach allows for faster and more precise delivery of tactile pressure stimuli comparing to the previously proposed vibrotactile stimulator–based approaches [3], [4] and it is not limited to finger tips only [6].

The goal of this study is to evaluate the performance of the novel tpBCI paradigm proposed and developed by our team. We present the concept of the novel tpBCI and results obtained with five healthy users tested in online BCI experiments.

The remainder of the paper is organized as follows. In the next section, the experimental setup and the tactile pressure paradigm are described, together with EEG signal pre–processing steps. Next, analysis and optimization procedures of the ERP $P300$ response latencies for all experimental users are described. Finally, classification and discussion of the tpBCI paradigm with information transfer rate (ITR) results conclude the paper, together with future research directions.

II. Materials and methods

The experiments in the reported study involved five healthy users (five males; mean age of 26.2 years, with a standard deviation of 10.0 years old). All the experiments were performed at the Life Science Center of TARA, University of Tsukuba, Japan. The online EEG BCI experiments were conducted in accordance with *The World Medical Association Declaration of Helsinki - Ethical Principles for Medical Research Involving Human Subjects*. The psychophysical and EEG recording for BCI paradigm experimental procedures were approved by the Ethical Committee of the Faculty of Engineering, Information and Systems at University of Tsukuba, Tsukuba, Japan (experimental permission no. $2013R7$). The participants agreed voluntarily to take part in the experiments and signed informed consents.

The details of the tactile pressure stimulus device, as well as the psychophysical and BCI EEG experimental protocols are described in the following subsections.

A. Tactile Pressure Stimulus Device

The tactile stimuli were delivered as light pressure patterns generated by a portable computer with a program developed by our team on the ARDUINO micro–controller board managed from our visual programming application MAX 6 [7]. Each

TABLE I. Details of the users participating in the experiments

User number	Sex	Age [years old]
#1	male	22
#2	male	24
#3	male	21
#4	male	20
#5	male	44
Average age		**26.2**
Age standard deviation		**10.0**

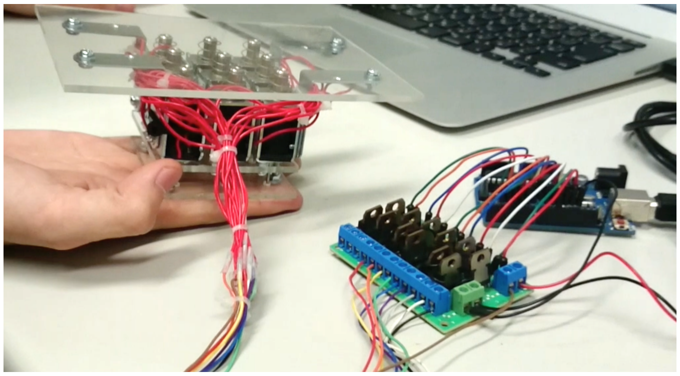

Fig. 1. The tactile pressure generator composed of the solenoids put on the user's dominant hand covering index, middle and ring fingers. These solenoids created six pressure patterns as explained in Table II. On the right side of the photograph the ARDUINO micro–controller board and the in–house developed multichannel amplifier are also depicted.

tactile stimulus was generated via the tactile pressure generator composed of nine solenoids arranged in the 3×3 matrix as depicted in Figure 1. The voltage binary outputs from the ARDUINO board were amplified by a multichannel amplifier developed also by our team as depicted in the right side of Figure 1.

There were six linear pattens of tactile pressure stimuli delivered in random order to the user fingers as shown in Table II. A symbol of $\otimes$ depicts stimulated position and $\odot$ non-stimulated one. Three of them $\#1$, $\#2$, and $\#3$ were horizontal lines ordered from the top to bottom of user's fingers respectively. The remaining patterns $\#4$, $\#5$, and $\#6$ were the vertical lines in left to right position order. The solenoids generated quick light pressures 100 ms long (see Table III with experimental condition details summarized).

During the both psychophysical and EEG experiments, the users positioned the tactile device on their dominant hand hand's fingers (right hand in case of all the users participating in this study) with a glove for preventing any electric noise originating from the device. The users responded (button press in psychophysical and mental confirmation/counting in case of EEG BCI experiment) only to the instructed pattern while ignoring the others. The training instructions were presented visually by means of the MAX 6 program designed by our team as depicted in form of an user interface display in Figure 2.

B. Tactile Pressure Psychophysical Experiment Protocol

The psychophysical experiments were conducted to investigate the influence of tactile pressure stimulus on the user behavioral response time and accuracy. The behavioral responses were collected using a trigger button on the keyboard and a MAX 6 program. The user was instructed which target stimulus to attend in each session by a red pattern shape of $\times$ symbols on the computer display as depicted in Figure 2 and summarized in Table II.

Each trial was composed of 100 ms tactile pressure patterns delivered to the user fingers in randomized order with an inter-stimulus-interval (ISI) of 900 ms. Every random sequence thus contained a single target and five non–targets. A single session was composed of ten runs for each tactile pressure target. The choice of the relatively long ISI was justified by a slow behavioral response in comparison to the EEG evoked potentials, as described in the next section. The tactile pressure psychophysical experiment protocol details are summarized in Table III.

TABLE II. STIMULUS TACTILE PRESSURE LINEAR PATTERNS USED IN PSYCHOPHYSICAL AND BCI EEG EXPERIMENTS. THE $\otimes$ SYMBOLS DEPICT ACTIVE (CREATING PRESSURE) AND $\odot$ THE PASSIVE SOLENOIDS (NO PRESSURE).

Pattern Number	**Linear Patten**
$\#1$	$\otimes\otimes\otimes$ $\odot\odot\odot$ $\odot\odot\odot$
$\#2$	$\odot\odot\odot$ $\otimes\otimes\otimes$ $\odot\odot\odot$
$\#3$	$\odot\odot\odot$ $\odot\odot\odot$ $\otimes\otimes\otimes$
$\#4$	$\otimes\odot\odot$ $\otimes\odot\odot$ $\otimes\odot\odot$
$\#5$	$\odot\otimes\odot$ $\odot\otimes\odot$ $\odot\otimes\odot$
$\#6$	$\odot\odot\otimes$ $\odot\odot\otimes$ $\odot\odot\otimes$

The behavioral response times were registered with the same MAX 6 program, also used for the stimulus generation and instruction presentation as depicted in Figure 2. The goal of the psychophysical experiment, investigating behavioral response times and target recognition accuracy in order to test an even distribution of cognitive loads (tasks difficulties) among the six tactile pressure stimuli, was reached and the results are discussed in the next section.

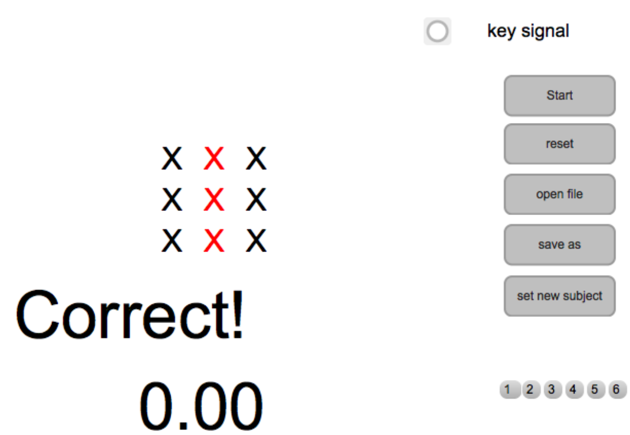

Fig. 2. The visual instruction screen presented to the users during the psychophysical experiment programmed in MAX 6 [7]. The red $\times$ symbols inform about the patten shape to be attended by a user in each experimental run.

TABLE III. TACTILE PRESSURE PSYCHOPHYSICAL EXPERIMENT CONDITIONS AND DETAILS

Condition	Detail
Number of users	5
Tactile stimulus length	100 ms
Inter-stimulus-interval (ISI)	900 ms
Stimulus generator	3×3 pressure pin matrix
Number of trials for each user	10

TABLE IV. CONDITIONS AND DETAILS OF THE TPBCI EEG EXPERIMENT

Condition	Detail
Number of users	5
Tactile stimulus length	100 ms
Inter-stimulus-interval (ISI)	400 ms
EEG recording system	g.USBamp active wet EEG electrodes system
Number of the EEG channels	8
EEG electrode positions	Cz, Cpz, P3, P4, C3, C4, CP5, and CP6
Reference electrode	Behind the user's left earlobe
Ground electrode	On the forehead(FPz)
Stimulus generator	3×3 pressure pins matrix
Number of trials for each user	10

C. EEG tpBCI Experiment Protocol

In the BCI experiments EEG signals were captured with a portable EEG amplifier system g.USBamp by g.tec Medical Instruments, Austria. Eight active wet EEG electrodes were used to capture brainwaves with event related potentials (ERP) with attentional modulation elucidated by the so-called "aha-" or P300-response. The EEG electrodes were attached to the head locations Cz, Cpz, P3, P4, C3, C4, CP5, and CP6 as in 10/10 intentional system [8]. A reference electrode was attached to a left earlobe and a ground electrode on the forehead at FPz position respectively. The users put on polyethylene gloves in order to limit any electric interference possibly induced by the tactile pressure generator placed on their hands. The users were also requested to limit their eye–blinks and body movements to avoid electromagnetic and electromyographic interference. Details of the EEG experimental protocol are summarized in Table IV. The EEG signals were recorded and preprocessed by a BCI2000-based application [9], using a stepwise linear discriminant analysis (SWLDA) classifier [10] with features drawn ERP interval of $0 \sim 800$ ms. The sampling rate was set to 256 Hz, the high pass filter at 0.1 Hz, and the low pass filter at 40 Hz. The ISI was 400 ms and each tactile pressure stimulus duration was 100 ms.

Each user performed three sessions of selecting the six patterns (a spelling of a sequence of six digits associated with each tactile pressure pattern). Each target was presented ten times in a random series with the remaining non-targets. A procedure of ten single ERP responses averaging was used to enhance the P300 responses.

III. RESULTS

This section presents and discusses results that we obtained in the psychophysical and in the online tpBCI experiments. The very encouraging results obtained in the tpBCI paradigm support the proposed new tactile interface concept.

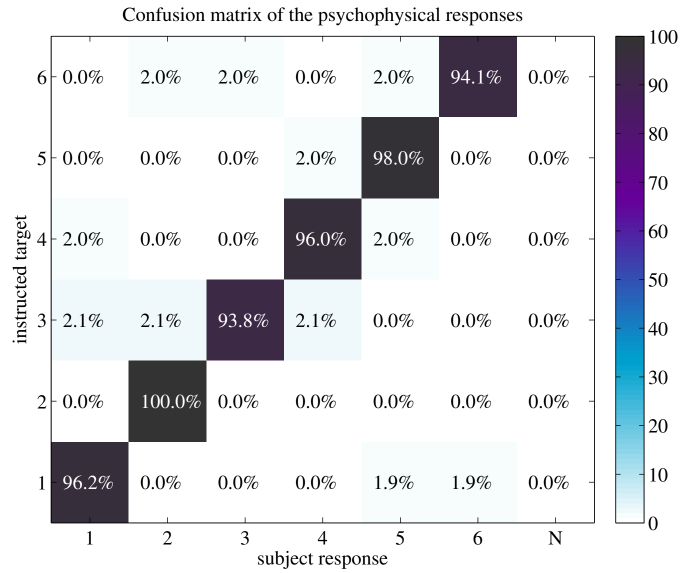

Fig. 3. Tactile pressure psychophysical experiment results in form of a confusion matrix of the grand mean averaged user accuracy results. The horizontal axis represents the instructed targets and vertical axis the user responses. N in the responses means "no–answer" condition, in which a user missed to push a keyboard. The off–diagonal responses and accuracies represent the marginal errors made by the users.

A. Tactile pressure psychophysical experiment results

The psychophysical experiment accuracy results are depicted in form of a confusion matrix in Figure 3, and as boxplot response time distributions in Figure 4, where the median response times and the interquartile ranges are depicted for each patterns respectively (see also Table II for the patterns).

This result confirmed the stimulus similarity since the behavioral responses for all the patterns were basically the same. This finding validated the design of the following tpBCI EEG experiment, since the six tactile pressure patterns resulted with similar cognitive loads as confirmed by the same accuracies and response times.

B. Online EEG tpBCI Experiment Results

The results of the conducted online tpBCI paradigm EEG experiment with the five users are presented in Figure 5 in form of matrices depicting ERP latencies with P300 response together with areas under the curve (AUC) feature separability analyses. We also present averaged topographic plots of the evoked responses at the latencies of the highest and lowest ERP separability in target vs. non-target scenario. The highest average difference was found at 422ms (as calculated by AUC), which perfectly represented the P300 response peak as could be seen also in Figure 6, where target and non-target response are visualized separately for each electrode. The online tpBCI accuracies (as obtained with SWLDA classifier) of the all five participating users are summarized in Table V. the four out of five users scored well above the chance level of 16%, which is a good outcome of the proposed tpBCI prototype. Based on the obtained accuracies we calculated to allow simply comparison of the proposed tpBCI paradigm with other published approaches, the ITR scores which were in the range

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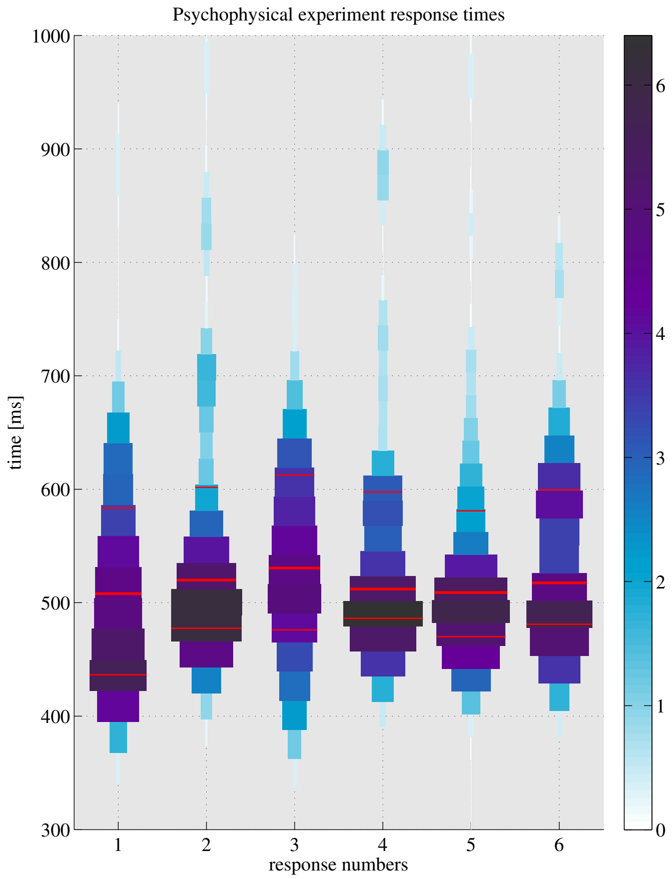

Fig. 4. Psychophysical experiment response time probability distributions of five users together summarized in form of distribution–shaped box plots depicting also medians and interquartile ranges. Each number at the horizontal axis represents the stimuli pattern. The horizontal axis represents the user reaction time delays in milliseconds.

from 0.16 bit/min to 3.83 bit/min (see Table VI). The ITR was calculated as follows,

$$ITR = V \cdot R \tag{1}$$

where V is the classification speed in selections/minute (2 selections/minute in this case) and R stands for the number of bits/selection calculated as,

$$R = log_2 N + P \cdot log_2 P + (1 - P) \cdot log_2 \left(\frac{1 - R}{N - 1}\right) \tag{2}$$

with N being a number of classes (six in this study); and P the classification accuracy (see Table V).

IV. Conclusions

The purpose of our research was to develop a six–commands–based tactile pressure BCI paradigm. We conducted psychophysical and online EEG BCI experiments to verify the efficiency of the proposed tactile pressure BCI with five healthy subjects. Results obtained from psychophysical experiments confirmed the tpBCI paradigm design validity.

TABLE V. Online BCI experiment SWLDA accuracy results from three experimental sessions conducted with each subject

User number	Session #1	Session #2	Session #3	Average score
#1	50.0%	33.3%	66.7%	50%
#2	33.3%	50.0%	33.3%	38.9%
#3	50.0%	50.0%	66.7%	55.6%
#4	0.0%	16.7%	0.0%	5.6%
#5	100.0%	88.3%	83.3%	90.6%
			Average	**48.1%**

TABLE VI. Ten trials averaging–based classification accuracy ITR results from three experimental sessions conducted with each subject

User number	Session #1	Session #2	Session #3	Average score
#1	0.84 bit/min	0.24 bit/min	1.78 bit/min	0.84 bit/min
#2	0.24 bit/min	0.84 bit/min	0.24 bit/min	0.40 bit/min
#3	0.84 bit/min	0.84 bit/min	1.78 bit/min	1.13 bit/min
#4	0.00 bit/min	0.00 bit/min	0.00 bit/min	0.16 bit/min
#5	5.16 bit/min	3.59 bit/min	3.59 bit/min	3.83 bit/min
			Average	**0.76** bit/min

According to the results obtained from the online EEG BCI experiments, a single user could score once with perfect accuracy and above 90% on average. Also one user balances below chance level on average. The remaining three users scored above chance levels. The preliminary, yet encouraging results support the initial research hypothesis of tactile pressure–based stimulus validity for the BCI paradigms.

The current paradigm obviously needs still improvements and modifications. However, even in its current form, the proposed tpBCI can be regarded as a alternative solution for LIS patients, who cannot use vision or auditory modality.

We plan to make the tactile pressure device smaller and more portable in near future. The users shall be able to enjoy the tpBCI more comfortably with possibly better accuracies. A demo with a video of the proposed paradigm with single trial averaging mode is available at [11].

Author Contributions

Designed and performed the EEG experiments, as well as analyzed the data: KS, HM, TMR. Conceived the concept of the tactile pressure BCI: TMR. Supported the project: SM. Wrote the paper: KS, TMR.

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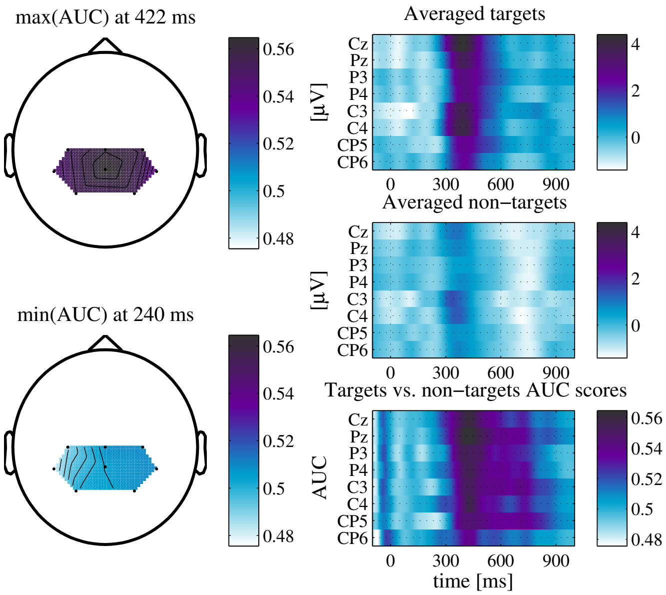

Fig. 5. Grand mean ERP and AUC score leading to final classification results of the all participating users. The left panels represent the head topographic plots of the target versus non-target area under the curve (AUC), which is a measure commonly used in machine learning intra-class discriminative analysis. ($AUC > 0.5$ is usually assumed to be confirmation of features separability). The first panel of the left side represents a head topographic plot with a latency of the largest difference as obtained from the data displayed in the bottom panel of the figure. The bottom right panel represents the smallest AUC latency. Those topographic plots also show the electrode positions. The fact that all the electrodes received similar AUC values supports the initial electrode placement. The first panel of the right side represents averaged EEG responses to the target stimuli (P300 response in the range of 300 $\sim$ 600 ms). The second from the top right panel represents averaged EEG responses to the non–target stimuli (no P300 response). Finally, the bottom right panel depicts the AUC of target versus non–target responses (P300 response latencies could be again easily identified here by purple color–coded values).

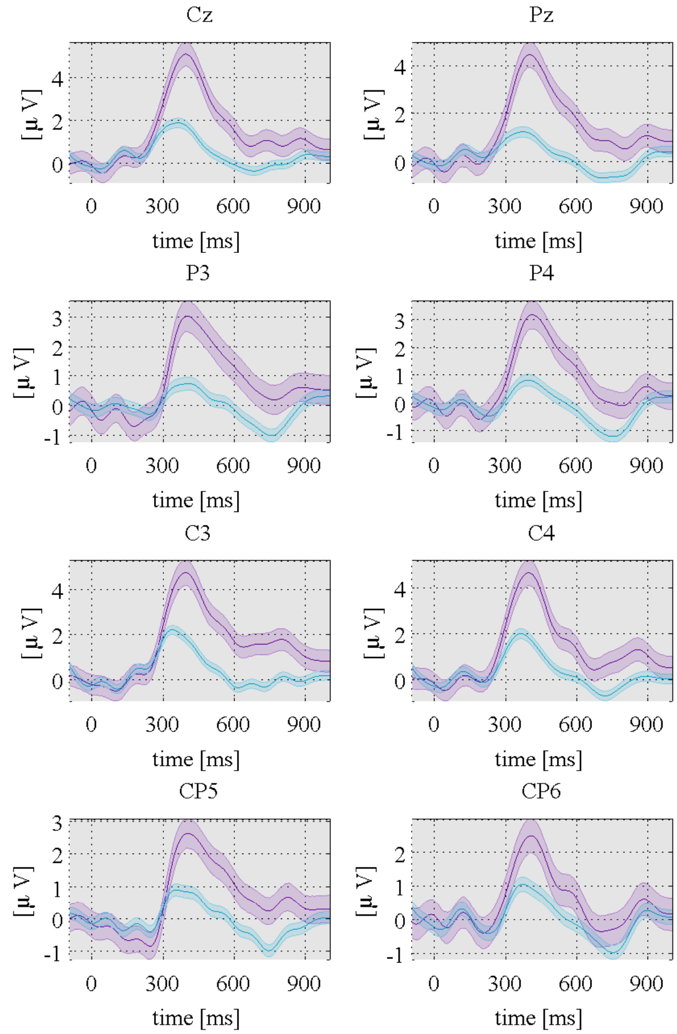

Fig. 6. Grand mean averaged ERP of all participating users. Each panel depicts responses from electrodes used in the study (see Table IV for details). The purple lines depict targets and blue non–targets respectively with standard error bars (standard deviation divided by $\sqrt{n}$, where n stands for a number of averaged trials). The clear P300 responses could be seen in the range of 300 $\sim$ 600 ms.

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