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MTI: a Motor Imagery Strategy Assisted by Tactile Imagery with Strong Correlation

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Abstract: In order to improve the performance of the brain-computer interface system of motor imagery (MI), the optimization of the MI strategy is an effective means. Therefore, this paper proposes a motor-tactile imagery (MTI) strategy to improve the classification accuracy of the MI-based brain-computer interface (BCI) system by adding a corresponding strong correlation of tactile imagery to each imaginary action of the MI. Electroencephalogram (EEG) signals generated by different strategies were collected, and the corresponding classification accuracy was obtained. The experimental results showed that the performance of the MTI-training group was significantly better than that of the MI group and the MTI-without-training group. The MTI strategy proposed in this study can significantly improve the performance of BCI.

Keywords: motor-tactile imagery (MTI); tactile training; brain-computer interface (BCI)

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0 Introduction

Despite over 30 years of research, the brain-computer interface (BCI) faces challenges, mainly due to low classification accuracy in electroencephalogram (EEG) signal processing. Even with advanced algorithms, if one user's imagery deviates from the established strategy, the best signal-processing techniques may fail to distinguish signals effectively. To address this, some researchers have added auditory, visual, or tactile^[1] cues to improve accuracy on the basis of motor imagery (MI), which relies on mental rehearsal to generate control signals without physical movement or external stimulation. But these methods often require extensive training and still yield the suboptimal result that EEG classification accuracy remains below 70% in about 30% of subjects.

Recent studies have shown that tactile stimulation can enhance MI-BCI performance by effectively activating relevant cortical areas and improving signal decoding^[1-2]. Whether used as a cue or feedback, tactile

input positively impacts MI-BCI control. However, similar to steady-state visual evoked potential (SSVEP) and P300 paradigms, it adds system complexity and may lead to user fatigue with prolonged use. Despite these, integrating tactile elements with the MI remains a promising approach to improving BCI accuracy.

Tactile imagery (TI) is fundamentally different from the above tactile stimulation in that TI can activate the corresponding cerebral cortex and generate EEG signals by imagining touch without being subjected to external stimulation of the actual physical world. Studies showed that the average accuracy of BCI signal recognition was 78.9% when subjects performed only the TI of the wrist^[3-4]. However, this accuracy rate is still unable to make the actual application of BCI relatively reliable, so this paper proposes a strategy that combines MI with TI, which is called MTI. This method adds logical and different TI contents related to the MI contents after the completion of the MI, which is to recover the cortical stimulus feedback during the physical realization of each imagined specific action as much as possible. The innovation of this method mainly lies in "strong correlation". Previous haptic correlation studies mainly focus on physical stimulation and imagining the stimulation of a certain part of the finger alone. Some studies don't combine MI, which are only single-element studies, while others don't have the attribute of "strong correlation", which are rather rigid and disconnected. MTI takes advantage of TI on the basis of MI and adds new features to make EEG signals easier to distinguish.

1 MTI Framework

1.1 Principles

On the premise that TI^[2] and tactile stimulation^[4] in specific left and right hand positions have been proven to be effective in improving the performance of the MI-BCI system, this paper proposes a MI strategy with the aid of strongly correlated TI based on the limb movement imagination strategy. Its principles are as follows.

1) The tactile sensation in the corresponding body parts after limb movement aligns with realistic logic and

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intuition.

2) Since Pacini bodies and Meissner bodies are spread throughout the body of healthy human beings, both realistic motion and mechanical vibration simulation can effectively trigger touch and provide a realistic basis for TI.

3) The motor cortex is very close to the sensory cortex, and certain TI signals already exist in the EEG signals of MI, but the corresponding TI has not been studied in previous experiments.

The content of TI studied in this paper is strongly related to the content of MI. Based on the physiological and physical laws of the real world, real limb movement is usually accompanied by tactile feedback of specific parts. The MI process of healthy subjects is itself accompanied by certain TI^[5], and this study amplified this feature (the left arm extended to the left and the left fist touched the obstacle), making the imagery content more realistic. The content of MI is difficult to unify due to the individual differences of users, but the training module in this study will unify the content of TI as much as possible, so that the subjects can perform the MI task more effectively. But from another point of view, even if MI and TI have a strong correlation, there is a significant difference between the two. MI is the active sensation of the subject, while TI is the skin sensation. There is a difference between spontaneous and passive generation. In fact, the objects of MI include limb muscles and limb joints, while TI only involves tactile perception of specific skin positions^[6]. Therefore, even though there is a strong correlation between MI and TI, it is still significant to study and emphasize them separately.

1.2 MTI strategy and training mode

MI is the cornerstone of MTI's research. In this paper, four kinds of MI actions are adopted. First, the subject moves his left arm from an initial coiled and tight position into a quick and straight punch toward his left side. Second, the right arm is extended straight to the right. Third, in the initial upright state, the left leg is kicked straight forward, stopping at about a 30° angle. The last, the right leg is kicked straight behind.

The four MI movements correspond to Figs. 1(a), 1(b), 1(c), and 1(d), in which the red dots are the occurrence points of TI and also are the working positions of the vibratory tactile stimulator during the MTI training.

As shown in Fig. 1, the corresponding TI is incorporated to form the MTI strategy, based on four types of MI. In this strategy, after extending their left or right hand into straight fist, the subjects imagine the tactile sensation of the four fingers on that hand touching a hard object with their dorsal phalanx. Similarly, while kicking with the left or right foot at a 30-degree angle, they imagine the tactile sensation of their left toe or right heel touching a hard object.

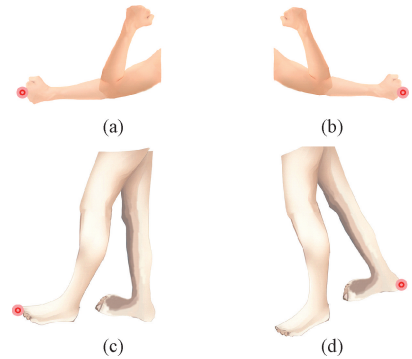


Fig. 1 Schematic diagram of MTI strategy: (a) MI moving left; (b) MI moving right; (c) MI moving upward; (d) MI moving downward

In MTI training, the subjects need to complete the following training tasks. 1) MI training should be completed first. As this experiment adopts the training method of visualizing and standardizing the imagined content of sports by relying on actual movements^[7], the actual activities of corresponding limbs are carried out according to the directional arrows on the computer screen during the training process. Then the MI training without physical activity is performed, and the process should be repeated ten times for reinforcement. 2) The designed vibratory tactile stimulator is placed on the four fingers of the left or right fist and the proximal dorsal phalanx muscle of the left toe or right heel of the subjects, respectively. The subjects need to complete the MI task within the specified period of time, and then the tactile stimulator is opened immediately to give the subjects physical stimulation. These processes last for 150 ms, and ten groups of training are conducted for each MTI content. 3) The subjects are asked to observe directional arrows on a computer screen for the MTI experiment without external stimuli. The subjects are asked to vividly reproduce the sense of touch in the corresponding skin area after the MI, and focus the imagery object on the corresponding skin area, as if the stimulation sensation emerged from the skin^[8]. After that, the prompt arrow is shuffled, and the subject continues training until the task is completed.

2 MTI Strategy Application

In order to verify the effectiveness of the proposed MTI strategy, three sets of experiments were designed in this study, namely the MI group, MTI-without-training group, and MTI-training group. The MTI-training group can avoid TI deviation caused by external factors such as individual differences. The MTI-without-training group serves as the control group to verify the necessity of pre-stimulus training, and the MI group serves as the control group to verify the contribution of TI to EEG signal classification.

2.1 Dataset creation

EEG signals were collected from 15 subjects (aged

20–40 years). None of the subjects had musculoskeletal injury or nerve damage, and none of them had ever done BCI training before this experiment. The use of the experiments described herein is non-invasive, does not cause additional risk or discomfort with study participation, and therefore does not require approval by an Ethics Committee.

EEG data were collected from a single-channel wireless electroencephalograph. The electrodes were worn on the left forehead of the subject. It is easy to get feedback from higher-order purpose-oriented cognitive brain signals. TI mainly activates the sensory cortex and motor control area of the basic body^[9-10], which corresponds to the prefrontal lobe of the brain. Throughout the recording process, the raw signal is digitally sampled at a frequency of 300 Hz.

In this experiment, a vibrator is designed to train subjects in the MTI-training group. The device can provide a 27 Hz sinusoidal wave modulated by a 175 Hz sinusoidal carrier for tactile stimulation^[11], and the experiments are carried out to determine the frequencies that can effectively activate Pacini bodies (activated above 100 Hz) and Meissner bodies (activated in 20–50 Hz).

2.2 Experimental process

The timeline of a single experiment is shown in Fig. 2. A total of 300 EEG signals were collected for each subject in each group.

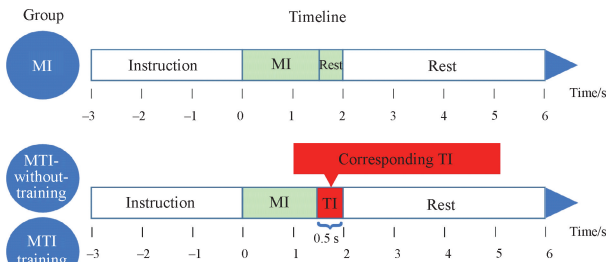


Fig. 2 Single experiment timeline of MI group, MTI-without-training group and MTI-training group

1) MI group

At the beginning of each set of experiments, a white cross appeared on the computer screen along with a timing progress bar, which lasted for 3 s while the subjects fixed their eyes on the white cross in order to concentrate. Then, left, right, up and down arrows (arrows corresponding to four kinds of MI actions) appeared on the computer screen, and the subjects needed to imagine the corresponding actions and collect EEG signals. The stage lasted for 1.5 s, that is, the MI signal acquisition stage. Then the rest period lasted for 4.5 s.

2) MTI-without-training group

In the MTI-without-training group, subjects directly performed the linkage imagery of motor and tactility without any physical vibrator training. The experimental process included 1.5 s of MI and 0.5 s of corresponding TI, and a rest stage lasting 4 s.

3) MTI-training group

The subjects received MTI-training (described in

Section 1.2) before performing this set of experiments. The imagery duration was 2 s (1.5 s for MI and 0.5 s for TI), and other experimental contents were consistent with those of the MI group.

Studies have shown that MI event-related desynchronization (ERD) typically peaks within 1–2 s, with an MI phase of 1.5 s sufficient to capture stable MI-EEG features. The TI phase of 0.5 s is designed to be performed immediately after MI, aiming to activate additional sensory cortex areas with TI. The tactile feedback is instantaneous, and the 0.5 s time reduces the mental burden of the subject for the imagination task under the premise of ensuring adequate response time.

Based on this design, the experiment comprises three types of tasks: MI, MTI without training, and MTI with training. Each performed in four directions (left, right, upward, and downward). Conditions are hereafter referred to by combining the direction and task abbreviation (e. g., left MI, right MTI-training, and upward MTI-without-training).

3 Experimental Analysis

3.1 EEG signal processing

Butterworth filter is used to filter and denoise the original EEG data collected in the experiment, leaving signals in the 8–30 Hz frequency band. The signals in this band include β waves and μ rhythms, which are the bands most associated with MI. After pre-processing, the collected EEG signals are processed by the fractional synchrosqueezing wavelet transform (FSSWT)^[12-13]. The time-frequency graphs (TFGs) of MTI-based and MI-based EEG signals obtained by FSSWT are taken as samples, and deep learning models are established based on ResNet50. The classification accuracy of the model is compared to verify whether the introduction of TI can effectively improve the performance of the MI-BCI system.

For the different experimental data generated by each subject, a single repeated-measure ANOVA was used to assess the differences in performance of MI, MTI-without-training, and MTI-training. When performance differences existed, a paired sample T-test (significance set as $\alpha = 0.05$) was used for further statistical analysis.

3.2 Experimental analysis results

The classification accuracy of MI, MTI-without-training, and MTI-training groups is shown in Table 1. The Shapiro-Wilk normality test was first used to determine whether the experimental data of classification accuracy were normally distributed. Under $\alpha = 0.05$ test level, for the MI group, $W = 0.975$ and $p = 0.924 > 0.05$; for the MTI-without-training group, $W = 0.909$ and $p = 0.131 > 0.05$; for the MTI-training group, $W = 0.963$ and $p = 0.744 > 0.05$. W represents the degree of fit to the normal distribution, and p is the significance index. The normal distribution was found at the test level of $\alpha = 0.05$.

Table 1 Comparison of classification accuracy of three imagery strategies

Subject	Classification accuracy/%		
	MI	MTI-without-training	MTI-training
1	72.26	74.46	78.22
2	85.08	84.72	86.10
3	68.36	74.18	76.98
4	92.36	92.98	93.00
5	80.18	83.24	83.80
6	98.26	96.72	98.22
7	65.02	73.28	76.14
8	74.68	76.40	80.26
9	68.98	76.26	84.14
10	76.88	74.18	72.98
11	82.36	89.82	90.28
12	80.18	79.24	82.46
13	76.34	79.26	76.88
14	83.72	86.68	89.22
15	85.16	90.24	92.48

After a single repeated measure, analysis of variance (ANOVA), there were significant differences among the three groups of data ($F(2, 42) = 26.043$, $p < 0.001$). Pairwise paired sample T-test (significance set as $\alpha = 0.05$) results are as follows.

1) The BCI classification accuracy of MTI-without-training was higher than that of MI group ($(82.11 \pm 7.71)\%$ vs. $(79.32 \pm 9.04)\%$, $t = -3.143$, $p = 0.007$).

2) The BCI classification accuracy of MTI-training was higher than that of MTI-without-training ($(84.08 \pm 7.36)\%$ vs. $(82.11 \pm 7.71)\%$, $t = -3.133$, $p = 0.007$).

3) The most significant difference was in the BCI classification accuracy of the MI group and MTI-training group ($(79.32 \pm 9.04)\%$ vs. $(84.08 \pm 7.36)\%$, $t = -3.755$, $p = 0.002$), which had the largest absolute value of t and the smallest p value.

It can also be easily found from Table 1 that even though some subjects have a low accuracy of BCI classification under the MI strategy (the accuracy is less than 70%), most of the classification accuracy has been significantly improved after TI is added (higher than 70%). The standard deviation (SD) values of the third subject (4.40), the seventh subject (5.77) and the ninth subject (7.58) were much higher than those of the other subjects in the single repeated measure ANOVA. This reflects that MTI-without-training and MTI-training can significantly improve the BCI classification accuracy.

Examining the FSSWT TFGs reveals distinct energy distribution patterns that further substantiate the superiority of the MTI strategy. For each TFG of left MI, MTI-without-training and MTI-training (Fig. 3) or upward MI, MTI-without-training and MTI-training (Fig. 4), the difference of feature distribution within the class is the least in the interval of 0–1.5 s. However, the MI group demonstrates an absence of time-frequency

energy distribution during the TI period (1.5–2.0 s) due to its resting state in this interval. In contrast, the other two groups containing TI components display varying degrees of energy enhancement and distribution pattern evolution in those TFGs.

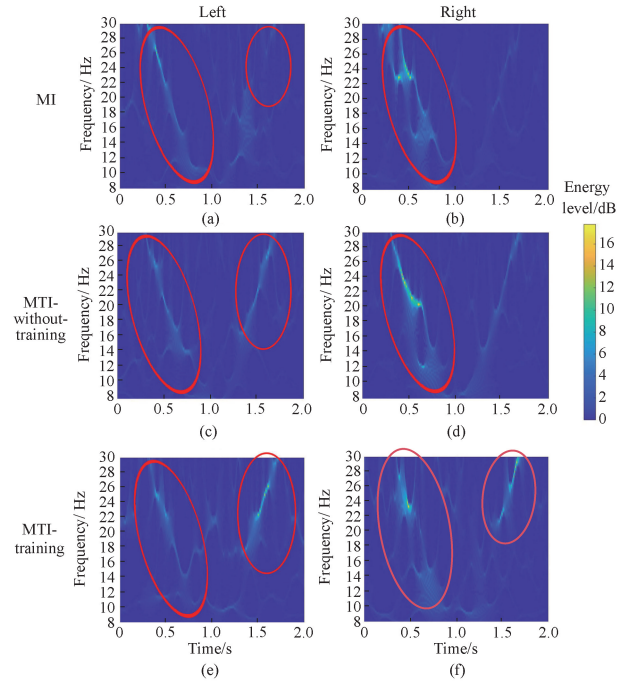


Fig. 3 Comparison of left and right FSSWT TFGs (the parameter a in the FSSWT method is set to 0.18): (a) left MI; (b) right MI; (c) left MTI-without-training; (d) right MTI-without-training; (e) left MTI-training; (f) right MTI-training

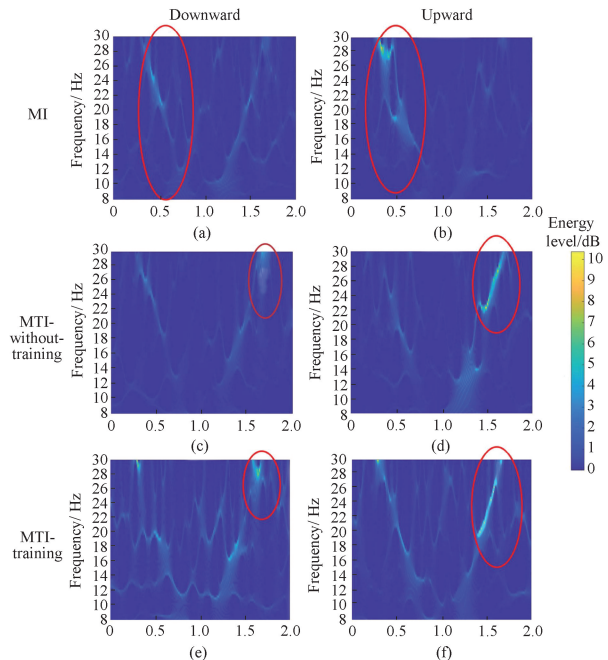


Fig. 4 Comparison of downward and upward FSSWT TFGs ($a = 0.18$): (a) downward MI; (b) upward MI; (c) downward MTI-without-training; (d) upward MTI-without-training; (e) downward MTI-training; (f) upward MTI-training

By comparative analysis of Figs. 4 (c) and 4(e) (or equivalently Figs. 4 (d) and 4 (f)), the trained group manifests more stable and discriminative time-frequency characteristics during the 1.5–2.0 s segment.

Integrating observations from Figs. 3 (e), 3 (f), 4(c) and 4(f), three key findings emerge.

1) Distinct differences in both μ rhythm and β wave frequency bands within the 0–1.5 s interval validate the effectiveness of the proposed MI strategy.

2) During the 1.5–2.0 s period, the incorporation of TI components induces energy aggregation and divergence in β wave regions (more closely associated with TI), thereby amplifying inter-class differences and enhancing BCI classification accuracy.

3) MTI training significantly improves the time-frequency response of TI signals, evidenced by the enhanced stability and discriminability in time-frequency distributions.

As shown in Table 1, for subject 10, the performance with MI is the highest, which indicates that the subject itself has a strong MI ability. Under the condition of adding tactile elements, if the features of TI are not distinguishable, it is likely to reduce the proportion of the time-frequency features of the original MI in the feature space. Other subjects, such as subject 13, may be able to integrate tactile information more naturally without training, but feel “stiff” or “deliberate” after training. In conclusion, these two results may not be a systemic problem in experimental design, but reflect the complexity and diversity of individuals’ MI, tactile integration, and their responses to training interventions.

4 Conclusions

In this study, MTI, a motor imagery strategy assisted by TI, is proposed to improve the classification accuracy of the MI-BCI system by adding corresponding TI to each imagery action of MI. The comparison results of simple MI, MTI-without-training and MTI training show that TI corresponding to imagery actions can significantly observe the changes of the cerebral motor cortex in EEG TFGs. And the performance of the MTI-based BCI system is significantly improved compared with that of the MI-BCI system, regardless of whether there is a precondition of physical tactile assistance training. Among them, the performance of the MTI-BCI system with physical tactile assistance training is more obvious, and the average value is significantly higher than that of the simple MI-BCI system. Future studies will include a wider range of age groups and continue to explore effective MI strategies without training.

References

[1] YU T Y, XIAO J, WANG F Y, et al. Enhanced motor imagery training using a hybrid BCI with

feedback[J]. *IEEE Transactions on Bio-Medical Engineering*, 2015, 62(7): 1706-1717.

[2] ZHONG Y C, YAO L, WANG J, et al. Tactile sensation assisted motor imagery training for enhanced BCI performance: a randomized controlled study[J]. *IEEE Transactions on Bio-Medical Engineering*, 2023, 70(2): 694-702.

[3] ZHANG X Z, GUO Y Q, GAO B Y, et al. Alpha frequency intervention by electrical stimulation to improve performance in mu-based BCI[J]. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 2020, 28(6): 1262-1270.

[4] YAO L, JIANG N, MRACHACZ-KERSTING N, et al. Performance variation of a somatosensory BCI based on imagined sensation: a large population study[J]. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 2022, 30: 2486-2493.

[5] KILTENI K, ANDERSSON B J, HOUBORG C, et al. Motor imagery involves predicting the sensory consequences of the imagined movement [J]. *Nature Communications*, 2018, 9(1): 1617.

[6] MOROZOVA M, NASIBULLINA A, YAKOVLEV L, et al. Tactile versus motor imagery: differences in corticospinal excitability assessed with single-pulse TMS [J]. *Scientific Reports*, 2024, 14(1): 14862.

[7] SENGUPTA P, LAKSHMINARAYANAN K. Cortical activation and BCI performance during brief tactile imagery: A comparative study with motor imagery[J]. *Behavioural Brain Research*, 2024, 459: 114760.

[8] YAKOVLEV L, SYROV N, MIROSHNIKOV A, et al. Event-related desynchronization induced by tactile imagery: An EEG study[J]. *eNeuro*, 2023, 10(6): ENEURO.0455-22.2023.

[9] BASHFORD L, ROSENTHAL I, KELLIS S, et al. The neurophysiological representation of imagined somatosensory percepts in human cortex [J]. *The Journal of Neuroscience*, 2021, 41(10): 2177-2185.

[10] SCHMIDT T T, OSTWALD D, BLANKENBURG F. Imaging tactile imagery: changes in brain connectivity support perceptual grounding of mental images in primary sensory cortices[J]. *Neuroimage*, 2014, 98: 216-224.

[11] BREITWIESER C, KAISER V, NEUPER C, et al. Stability and distribution of steady-state somatosensory evoked potentials elicited by vibrotactile stimulation [J]. *Medical & Biological Engineering & Computing*, 2012, 50(4): 347-357.

[12] GUO Y, LI B Z, YANG L D. Novel fractional wavelet transform: Principles, MRA and application[J]. *Digital Signal Processing*, 2021,

- 110; 102937.
- [13] DAUBECHIES I, LU J F, WU H T. Synchronsqueezed wavelet transforms: an empirical mode decomposition-like tool [J]. *Applied and Computational Harmonic Analysis*, 2011, 30(2): 243-261.

触觉运动想象：一种强关联触觉意象辅助的运动想象策略

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摘要: 为提高运动想象脑机接口系统性能, 优化运动想象(motor imagery, MI)策略是一个有效的手段。该文提出了一种运动-触觉想象(motor-tactile imagery, MTI)策略, 通过为运动想象的每一个想象动作添加对应强关联触觉想象以提升基于运动想象的脑机接口(brain-computer interface, BCI)系统分类准确度。收集了不同策略产生的脑电图信号, 并分别获取相应的分类准确率。试验数据结果表明, MTI-训练组准确率显著优于MI组和MTI-无训练组。该研究所提出的运动-触觉想象策略能够显著提高脑机接口的性能。

关键词: 触觉运动想象; 触觉训练; 脑机接口