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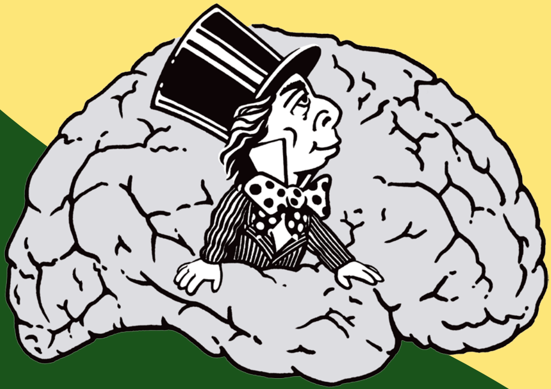

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THE MECHANISMS OF VISUOMOTOR TRANSFORMATION AND DEVELOPMENT OF A NEW BCI PARADIGM

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Abstract. Visuomotor transformation is crucial for achieving various goals during activities of daily living. This function can be impaired by stroke and other brain disorders. Although optimization issues remain, brain-computer interfaces (BCIs) have proven effective as a stand-alone or combined therapy for post-stroke patients. Our previous work on visuomotor transformation-based BCI paradigms demonstrated evidence of motor improvements. These results are encouraging, but with the current EEG-based BCIs, it is hard to assess the neuronal mechanisms of the transformation of visual input into upper-limb movements, mostly because the stimuli and movements are far apart in time. This is a serious impediment, because monitoring changes in visuomotor transformation is crucial for the success of treatment. Here we introduce a fast visuomotor task where participants reach toward buttons located at different distances or imagine these movements. EEG recordings revealed that visuomotor transformation, assessed using motor-related potentials (MRPs), differed depending on the distance to the target. We suggest using this paradigm for dissociating different stages of visuomotor transformation, including the translation of visual information into motor-preparatory and motor-execution activities. Moreover, conducting EEG analysis for imagined movements makes this paradigm highly relevant to BCI rehabilitation practices.

Keywords: visuomotor transformation, brain-computer interface, EEG, motor execution, motor attempt, motor imagination, stroke, neural correlates

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Introduction

Visuomotor transformation is a neuronal mechanism through which visual information is converted into a motor command. Through these processes, we are able to reach and grasp different objects in everyday life. Diseases that affect brain function, such as stroke, impair this function and result in poor quality of life. The limitations of conventional therapy for this impairment include dependence upon the patient's residual muscle strength and a lack of neurofeedback (Frolov et al., 2017; Orban et al., 2022), all of which hinder treatment efficacy. Other approaches, such as the use of robotics or virtual reality, are effective as rehabilitation tools but are hard to assess neurophysiologically because measurements of a patient's brain activity tell little about the ongoing neuroplasticity (Sebastian-Romagosa et al., 2017).

Though brain-computer interface (BCI) has appeared to improve the current treatment, it is also suffering some hitches, such as the accuracy of catching patient intentions and the stability of the system (Frolov et al., 2022). Owing to the fact that our motor behaviors are sensorily driven, there is a need for the development of a BCI such as visuomotor transformation based BCI that could fit this purpose. According to EEG studies, the amplitude and latency of evoked potentials such as visual and motor-related potentials (MRPs) indicate brain activity during a visuomotor transition task. Specifically, the early components of event-related potentials (ERPs) represent processing of visual information about the external target, whereas the late component represents cognitive processing and action preparation and execution. Motor-related processes are represented by the lateralized readiness potential (LRP) and the reafferent potential, which reflects afferent processing (Ibanez et al., 2012). Reaching and grasping are the parts of our daily tasks, and reaching for distant and near targets is known to require activation of different muscle groups and a different number of joints and contraction force (Furmanek et al., 2019). So, it is believed that preparation to different motor acts has to be reflected in MRPs before and during the execution. LRP has been found to be larger when complex actions are planned, which was supposed to be related to the number of engaged muscles. However, specific markers of visuomotor transformation that can be used in BCI control are still unknown.

Here, we developed an experimental paradigm where participants reached toward buttons and pressed them. The buttons located at close or distant positions enabled us to experimentally manipulate the process of visuomotor transformation. This approach proved to be efficient for monitoring how visual information translates into an appropriate movement pattern. Therefore, this study adds to our understanding of the neural correlates of visuomotor transformation. Moreover, we show how classifiers could be fit to decode movement intention from the EEG patterns — a finding relevant to BCI implementations.

Methods

We recruited 10 participants (3 females and 7 males). The participants were seated in front of a panel with two buttons located at different positions. The participant placed his right hand in a starting position. The first button was located at a distance of 10 cm from the participant (close target) and second was placed at 40 cm (far target). Three experimental conditions were performed: motor execution, where participants performed real movements (RM) to reach and press the target button, motor attempt (MA), where the participants performed muscle contractions in an attempt to reach the target, or motor imagery (MI), in which the participants kinesthetically imagined reaching and pressing. The cue for a particular target was delivered by a sequence of 3 flashes of the target button; thereafter, the targets flashed together, but the participants were instructed to reach toward the button designated as the target and ignore the non-target. There were six ran-

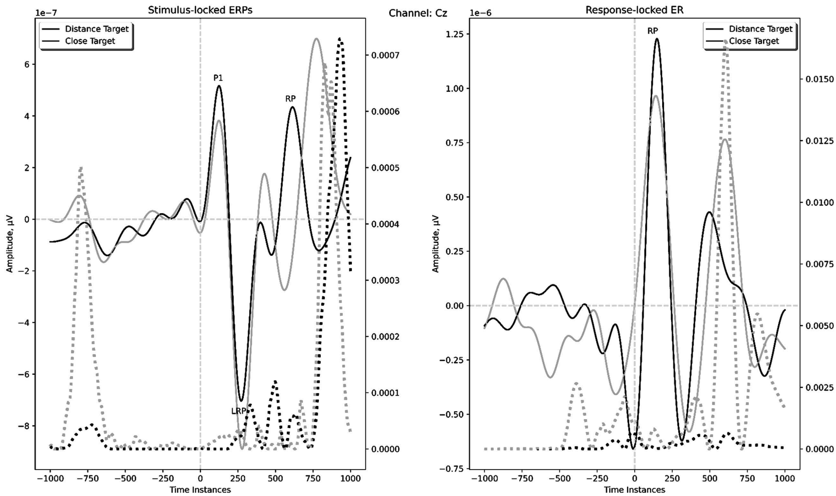

Figure 1. Stimulus- and response-locked ERPs during real movement for reaching and pressing close (gray line) and distant (black line) targets. The dotted line of the corresponding color indicates the EMG

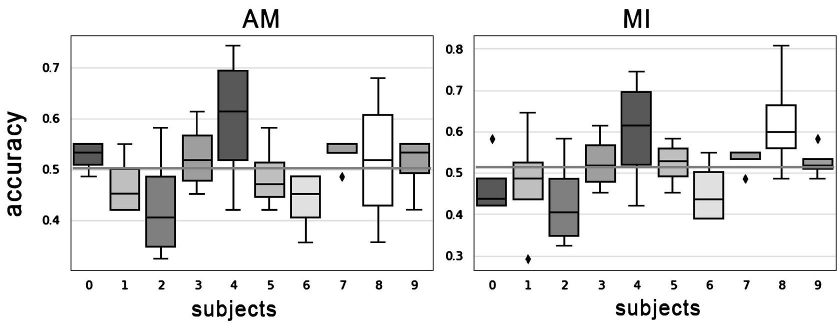

Figure 2. Subject based classification for attempted and imagined movement (Close versus Distant)

dom sessions, two for each paradigm, each lasting for seven minutes. The signal was acquired using NVX-36 with 30 EEG electrodes and 1 EMG electrode placed at the flexors of the elbow. In the subsequent data processing we used independent component analysis (ICA) to remove artifacts and filtered the signal with a band-pass filter of frequencies 1 – 10 Hz. The signal was epoched by [– 1 – 1 s] epochs with [– 0.5 – 0 s] interval for baseline correction. For the purpose of classifying the signals into either RM or MI, we used training epochs from 0 – 0.7 s based on several trials. Common spatial patterns (CSP) and SVM were used to extract and classify features from all channels and from each participant.

Results

A cross-subject average ERP for RM task was computed to analyze the stimulus-locked and response-locked cortical potentials for close and distant targets. The result is displayed in Fig. 1. The obtained potentials reflect visuomotor transformation as they contain the ERP components involved in the process; P1, LRP, and reafferent potential (RP). A permutation test revealed three significant clusters, which differentiated the close and the distant target at around 0.2 – 0.6 s and 0.8 – 1 s in the stimulus locked response ($p \leqslant .05$). The classification accuracy ranges from .30 to .80 for attempted movement and .32 to .80 for imagined movement (Fig. 2). This low accuracy might be related to the ambiguous nature of these movements compared to real movement.

Discussion

In this study we showed that varying the distance to a target of reaching movement resulted in clear changes in the shape and amplitude of cortical potentials. With respect to the amplitude effects, Fomin et al. (2010) suggested that high amplitude of cortical potentials translated to a stronger muscle contraction, which in our case was needed for reaching distant targets. Indeed, we found that in the stimulus locked ERPs, the P1 component of the potentials corresponding to the distant target was higher than that of the closer target, indicating that the visual cortex might be more active when processing the distant target but in the response locked, the amplitude remained almost the same. This result could mean that, since the reaction time for closer targets could have been faster, there was a need for higher LRP amplitude and, as such, a need for modulation of the P1 component. In fact, earlier studies have shown a link between the early visual processing of a stimulus and the magnitude of readiness potential (Benedetto et al., 2022).

While LRP reflects the motor cortex activation during planning and ends immediately before the execution, RP appearing during execution and related to a target reaching might be related to motor performance evaluation by somatosensory cortices (Ibanez et al., 2012). We found RP related to motor execution to be higher for the closer target compared to the distant target for both stimulus- and response-locked potentials. This observation might indicate that the sensorimotor areas are more active when movement is directed towards a closer target despite the fact that this movement requires a smaller number of muscles. However, as these MRPs are the result of averaging several trials, we also hypothesize the less variability in time spent for reaching close targets. This result also points to the differences in reaction time for the distant and close targets (Omura et al., 2015). Another possible explanation is that confidence in performing movement might have influenced the observed differences in the amplitude of the MRPs (McAdam, Rubin., 1971). In fact, the higher the confidence, the higher the amplitude, and based on this notion, we could infer that the participants had a higher confidence in pressing the closer button.

We also observed differences in ERP peak amplitudes in the AM and MI conditions. Initially, we tried to fit the classifier offline to separate single trial EEG epochs related to near and far targets in both conditions. There were a few subjects whose single trial responses could be correctly classified. Further, we will try to use multiple epochs for prediction to increase the accuracy and efficiency of the BCI. We will also test the online paradigm of BCI control.

Overall, these results suggest that varying the target distance for both real and imagined movements can be used as a method to modulate cortical potentials in a controlled manner, which in turn may be useful for the development of visuomotor transformation-based BCIs for motor rehabilitation.

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ИССЛЕДОВАНИЕ МЕХАНИЗМОВ ЗРИТЕЛЬНО-МОТОРНОЙ ТРАНСФОРМАЦИИ И РАЗРАБОТКА НОВОЙ ПАРАДИГМЫ ИМК

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Аннотация. В повседневной жизни зрительно-моторная трансформация играет решающую роль в обеспечении целенаправленных движений. Эта функция может быть нарушена при инсульте и других заболеваниях головного мозга. Несмотря на существующие проблемы с оптимизацией, интерфейсы мозг-компьютер (ИМК) доказали свою эффективность в качестве самостоятельной или комбинированной терапии для пациентов, перенесших инсульт. Наша предыдущая работа над парадигмами ИМК, основанными на зрительно-моторной трансформации, продемонстрировала их вклад в восстановление двигательной сферы. Хотя эти результаты обнадеживают, существующие ИМК на основе ЭЭГ с трудом позволяют оценить нейронные механизмы преобразования зрительной информации в движения верхних конечностей, в основном из-за того, что стимул и движение сильно разнесены во времени. Это серьезная проблема, так как возможность отслеживать изменения в зрительно-моторной трансформации крайне важна для успеха лечения. В этом исследовании мы провели эксперимент, в котором задачей участников было дотягиваться до кнопок, расположенных на разном расстоянии, или представлять себе эти движения. Анализ ЭЭГ показал, что зрительно-моторная трансформация, оцениваемая с помощью моторных вызванных потенциалов, различалась в зависимости от расстояния до цели. Мы предлагаем использовать эту парадигму для выделения этапов зрительно-моторной трансформации, в том числе трансформации зрительной информации в подготовку и реализацию движения. Кроме того, проведение анализа ЭЭГ для моторного воображения делает эту парадигму актуальной для практического применения в реабилитации с помощью ИМК.

Ключевые слова: зрительно-моторная трансформация, интерфейс мозг-компьютер, ЭЭГ, движение, двигательная попытка, двигательное воображение, инсульт, нейронные корреляты

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