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SHOULD ATTEMPTED MOVEMENTS REPLACE MOTOR IMAGERY IN BCI? THE ISSUE OF COMPATIBILITY WITH GAZE USE

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ABSTRACT: Attempted movements have recently become common in invasive studies as a way to send commands via BCIs and have been successfully employed in some studies of neurorehabilitation using noninvasive BCIs. Nevertheless, they are still far less common in noninvasive BCIs than motor imagery. We proposed a hypothesis that attempted movements can be more compatible with the interaction with the external world than imaginary movements and therefore may help to use BCIs more effectively. The hypothesis was tested in 15 healthy participants who were asked to make prosaccades, which represented an external task, and quasi-movements (movement attempts minimized down to complete extinction of related muscle activation), which were used as a model of attempted movements. Preliminary results of the study were mostly in line with the predictions, although more studies are required for more definite conclusions. The study also may be considered as a new demonstration of the potential of quasi-movements, a very little explored phenomenon, for BCI research.

MOTOR IMAGERY IN BCI

Motor imagery based brain-computer interfaces (MI BCIs) [1] employ the sensitivity of the EEG sensorimotor rhythms (mu rhythm and sensorimotor beta rhythms) to the imagination of movements and are currently among the most popular noninvasive BCIs. Their accuracy is rather low but can be improved to some extent through training [2]. In addition to assistive technologies, application of MI BCI to neurorehabilitation, especially post-stroke rehabilitation, was addressed in many studies (for reviews, see [3, 4]).

The case of hybrid eye-brain control – Among other attempts to improve MI BCI efficiency are combining it with gaze-based control. Recently, the success of the Apple Vision Pro headset demonstrated that the combination of gaze-based control with hand gestures can be effectively used in AR/VR even by healthy individuals [5]. However, gaze-and-MI-BCI control so far was successful mostly when the use of gaze and EEG modalities were relatively independent [6, 7], while their tight integration proved difficult [8, 9].

MOVEMENT ATTEMPTS IN BCI

Like motor imagery, movement attempts in paralyzed individuals are accompanied by distinct desynchronization of their EEG sensorimotor rhythms, with spatiotemporal pattern similar to observed when a healthy person makes a real movement. In some early studies of BCI-based neurorehabilitation patients were asked to attempt to make movements, rather than to imagine them (e.g., [10]). This approach has again attracted certain attention recently, when several studies demonstrated better outcomes for attempted compared to imagined movement BCI (see [11, 12] for meta-analyses). Attempts to move were also successfully used by patients in a number of recent high-profile studies of invasive BCIs developed for assistive purposes movement [13, 14, 15, 16] and even in combination with gaze-based cursor control, which was implemented in the first clinical trial with the endovascular BCI [17].

CONTROVERSY BETWEEN EXTERNAL ATTENTION AND IMAGERY

In active BCIs, either for assistive or rehabilitation purposes, feedback from a BCI plays an important role, informing a patient about the current course of action, helping them to correct control strategies and enabling effective training. However, focusing on imagery means that attentional resources are directed to a mental, internal task, and a BCI user needs to divide their attention between it and feedback that comes from the external world. This need to divide attention remains when not only visual but also haptic or auditory feedback is used, and even though a BCI is normally controlled via kinesthetic imagery (visual imagery is not effective for modulating sensorimotor rhythms). In any case, with the only exception for direct brain stimulation, a BCI is activated by merely mental actions and the feedback is provided via sensory stimulation. Moreover, even when the feedback is mostly haptic (e.g., in exoskeleton-assisted post-stroke rehabilitation), visual attention still may be strongly involved. The controversy seems especially severe when a MI BCI is combined with gaze-based control, where gaze should be intentionally controlled at the same time when motor imagery is executed.

Recent psychophysiological studies indicate that dividing attention between internal and external tasks and instructions for gaze during internal tasks may indeed hinder performance [18, 19] (see also references

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in [19]). It was also found that an imagery task took longer time during instructed eye fixation than under free eye movement condition [20]; note that gaze control and external attention are strongly connected.

WHY ATTEMPTED MOVEMENTS MAY BE A SOLUTION?

As we noted above, growing evidence indicates that attempted movements may work better in BCI than motor imagery. In the view of the conflict between external and internal tasks, one possible reason could be that attempted movements are not a typical internal task. In an attempt to make a movement a healthy individual is intending an interaction with the external world. A paralyzed individual knows that the attempt will not lead to such interaction, but their intention and effort may not differ dramatically from a healthy person's intention and effort. The ability to imagine a movement may be much different, as it developed in the course of evolution as an ability to simulate reality, not to actually interact with the external world.

QUASI-MOVEMENTS AS A MODEL OF MOVEMENT ATTEMPTS FOR STUDIES IN HEALTHY PARTICIPANTS

Studying attempted movements in healthy participants is not a trivial task, since normally attempts lead to actual movements, and related sensory activation changes the EEG dramatically. Constraining a limb (e.g., [21]) changes the pattern of this afferent stream, but evidently cannot exclude sensory activation during attempts. Temporal artificial paralysis is an effective solution [22], but this approach cannot be widely used.

Fortunately, a way to teach healthy participants to make movement attempts without muscle activation exists. Such movement attempts, made by non-paralyzed individuals without actual movement and muscle activation, are called quasi-movements (QM) [23]. They appear when a person is asked to make smaller and smaller movements and to further weaken the attempts to a degree when the electromyogram (EMG) becomes indistinguishable from rest level. Importantly, the EEG activation pattern remains in QM similar to that in overt movements and in IM, and activation in QM is stronger than in IM [23]. QM are not an ideal model of attempted movements, because they model only weak movement attempts, and, even more importantly, require special attention to keep them weak. Nevertheless, due to the lack of good alternatives it might be still important to study this model.

Recently, we showed that QM provides stronger activation than IM independently of residual muscle activation [24]. Moreover, our participants mostly reported that their intention in QM was to make a movement rather than to imagine it [25], which confirms the assumption by [23] that they may serve as a model for attempted movements. However, to our knowledge, no study of possible differences between QM (as well as other types of attempted movements) and IM from the point of view of internal vs. external orientation of cognitive resources has been undertaken so far.

INTERNAL OR EXTERNAL TASK? AN EXPERIMENTAL ASSESSMENT

No standard procedure was adopted so far for assessing whether a mental task is more internal or external. In [19] interference between internal, mental tasks (arithmetic and visuospatial) and an external task (prosaccades, i.e., saccades to a target, in the presence of a distractor) was assessed quantitatively. We decided to use their experimental design, with some modifications, to compare kinesthetic IM and QM in terms of their external or internal nature. More specifically, we asked our participants to make prosaccades at the same time intervals when they performed IM or IQ, to assess the degree of interference in each case (presumably related to the need to divide attention between the tasks).

Study hypotheses – We hypothesized that under QM condition, compared to IM condition, subjective difficulty will be lower, accuracy of eye movements will be higher. In addition, for the case if subjective difficulty indeed were lower or same in QM as in IM, we expected that EEG modulation would be more pronounced under QM than in IM. In other words, we expected that IM, as a clearly internal task, will interfere more with prosaccades (an external task) than QM, due to the more external nature of QM compared to IM.

METHODS

Participants – 15 healthy volunteers (8 female; age 18 to 38, median 23) participated in this study after signing an informed consent. Data from four of them were excluded from the analysis due to eye tracking issues or other technical issues.

Apparatus and software – Stimuli were presented at a 60 Hz 24" AOPEN 25XV2Q monitor with 1920x1080 resolution in front of a participant. Gaze data were acquired at 1000 Hz rate with EyeLink 1000 Plus eye tracker (SR Research, Canada). 64-channel EEG, one-channel electromyogram (EMG) from *m. abductor pollicis brevis* and a signal from a photo sensor on the screen (used to precisely synchronize with visual stimuli presentation) were recorded at 1000 Hz sampling rate with 0…300 Hz passband using the NVX136 DC EEG amplifier (Medical Computer Systems, Moscow, Russia). EMG was monitored online as a raw signal and after transforming with the Teager-Kaiser energy operator (to highlight deviations from baseline level). Stimuli presentation, data acquisition, synchronization, online processing and recording were done with *Resonance* platform [26] and additional modules written in Python.

Experiment design – Two sessions were run on different days. In the first session, participants were

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introduced to the basic movement (right thumb abduction, as in [23], but made in triplets – like in [24], but self-paced) and trained to make IM and QM according to procedure by [23] with modifications described in [24]. The EEG was recorded under single-task QM and IM. The single saccade task (ST) and the dual tasks (ST combined with OM, IM and QM) were in the second session, with the order of IM and QM dual tasks randomized over the group (contrast between these two dual tasks was the main part of the experiment, while the other conditions provided various additional data). In both sessions, the EEG was also recorded under overt movements of the same type and under visual task, to obtain data for CSP spatial filter training; the visual task also helped to regain a baseline sensorimotor rhythm level (see [24], for details).

Procedure – All participants were naive to QM. Following [23], we did not reveal to them that they did not actually make movements (their right hand was covered with an opaque case). QM and IM quality was controlled using online EMG control (if EMG increase was observed, participants were asked to relax in IM or to further reduce QM) and using offline EEG analysis. Trial structure is presented in Fig. 1A for single tasks and in Fig. 1B for dual tasks. Targets and distractors for the ST were presented at the same distance from the fixation cross at random positions, but close to each other, following [19].

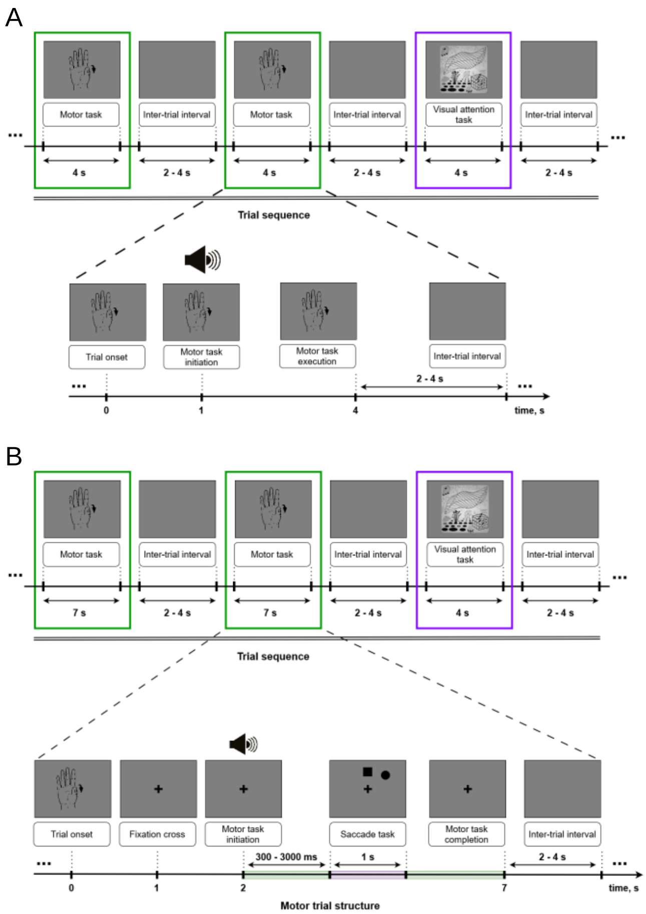

Figure 1. Trial structure in (A) single and (B) dual tasks.

In the beginning of each dual-task trial a fixation cross appeared in the center of the screen. After 2 s a sound signaled to start the sensorimotor task (OM, IM or QM). Participants were asked to fixate on the cross until (after a random time interval) a target and a distractor appeared (for half of the group, they were circle and square, relatively, and for another half, vice versa), when they had to make a saccade to the target as soon as possible. As in [19], they were free to continue the internal (here, sensorimotor) task at this time or to return to it after making a saccade on the target but had to complete it anyway. (See Fig. 1 for additional details).

EEG and EMG analysis followed [24]. As the baseline for ERD/ERS computation, however, here we used a 500 ms interval preceding the fixation cross presentation. We also did not use here special procedures for removing possible contribution of residual muscle activation to brain activation, because in the current study the EMG was stricter controlled during the experiment than in [24], and because we already shown in [24] that small residual EMG increases in some trials in this task are not related to any substantial EEG effect. We refrained from assessing performance of BCI classifiers on the EEG data, because it would very likely just mirror the effects observed in the averaged data and because we plan to assess classification performance in an online hybrid BCI experiment, which could serve as a much more relevant model.

Eye movement analysis – Fixations were considered maintained on the fixation cross in the dual-task trials if they did not depart from it further than 1° before the saccade. Saccade latency was computed as time between target presentation onset and saccade onset. Saccades were considered as landing on a target/distractor if they ended within 2° from them.

RESULTS

Task difficulty – Participants were asked to indicate whether IM+saccades or QM+saccades condition was more difficult, using a visual analogue scale (VAS). With 0 corresponding to more difficult QM+saccades and 1 to IM+saccades, M±SD was 0.66±0.34, median=0.83. Only one participant found no difference between the conditions, and four reported QM+saccades as more difficult; importantly, all those four had difficulties in mastering the QM, and three of them reported that the problem for them was avoiding pronounced movements.

Gaze performance in dual-tasks with IM was only slightly (insignificantly, according to Wilcoxon paired test) lower than in dual-tasks with QM, although the difference was in favor of QM for all three analyzed indices (Figure 2).

EEG results – Group averaged time-frequency plots for strongest individual contralateral alpha band sources of the EEG sensorimotor rhythm are shown in Fig. 3. Stronger alpha band desynchronization was observed in

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QM compared to IM dual task conditions (compare QM_{ST} vs. IM_{ST} in Fig. 3).

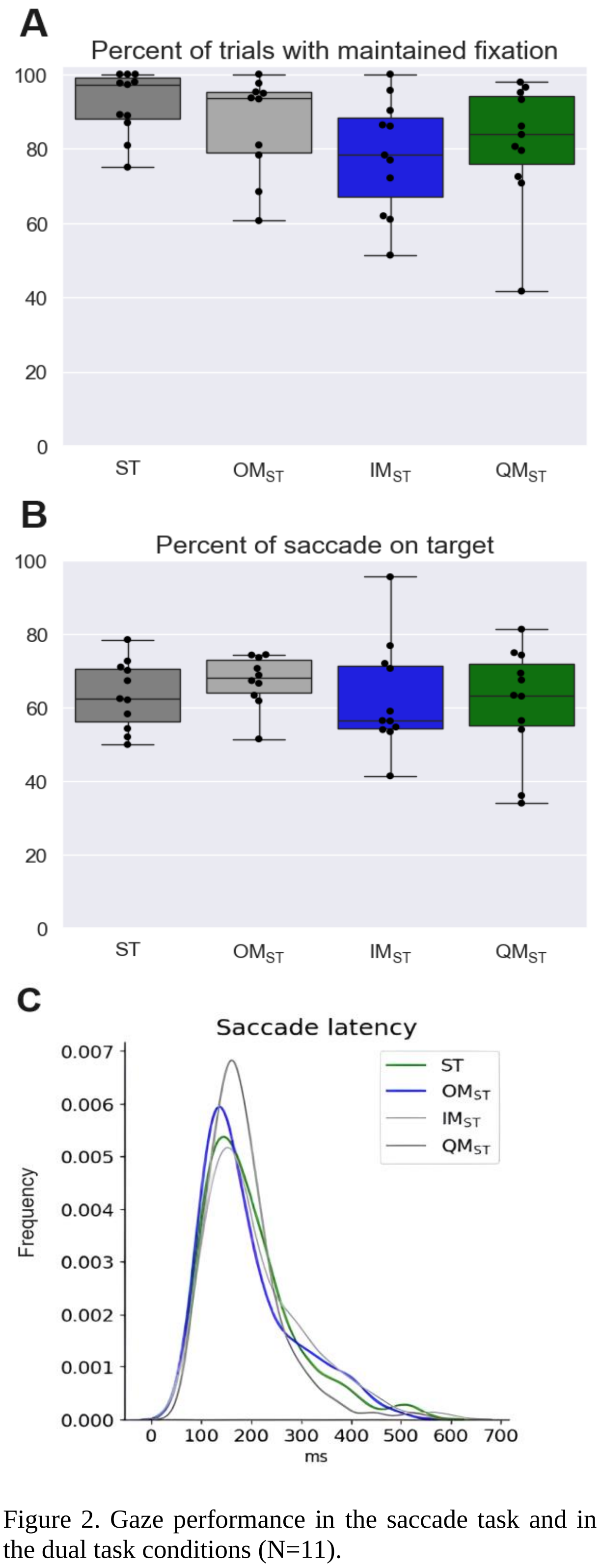

Figure 2. Gaze performance in the saccade task and in the dual task conditions (N=11).

DISCUSSION

The experimental results reported above should be considered as preliminary, due to the limited number of participants and incomplete analysis. All observed tendencies were in favor of our hypotheses, i.e., were in line with the assumption that attempted movements, modeled here with quasi-movements, are more compatible with intentional gaze use than kinesthetic motor imagery. However, most differences did not reach statistical significance. We are planning to collect data from 10 more participants and to refine the analysis, to get to more definite conclusions. Still, at the current stage attempted movements were confirmed to be at least as effective as motor imagery commonly used in noninvasive BCIs.

Note that quasi-movements are a most minimized form of attempted movements, requiring lowest "motor" effort (apart from additional cognitive control required to prevent movement). To fully understand the potential of attempted movements, it also may make sense to explore them more in paralyzed patients, amputees, and using the constrained movement paradigm [21], where effort can be much stronger. Nevertheless, studies of quasi-movements, featured with an unique combination of attempt to move and absence of any physical effect in people that are able to make movement [23, 25], may significantly enrich the whole picture.

Interestingly, the most common complaint from our participants about the quasi-movements was that it was difficult for them not to make a pronounced movement. Note that in paralyzed patients this is not an issue in most cases, especially in neurorehabilitation, where making a real movement instead of just trying to make it is the goal of training.

Attempted movements have certain features that are helpful from a practical point of view. In particular, they can be more easily explained to many paralyzed individuals than kinesthetic imagery (its training often starts in healthy participants from making overt movements!) and seem to require far less training to produce clear EEG patterns. However, studies are needed to understand if attempted movements, including quasi-movements, can elicit the same or higher EEG effects as imagery after significant time of practice. For quasi-movement, it is also important to study various movements: so far, only thumb abduction was explored in all studies, partly due to the assumed need to precisely control EMG (but this may be not really important, as our previous study showed no contribution of residual muscle activation in quasi-movements to EEG effects [24]).

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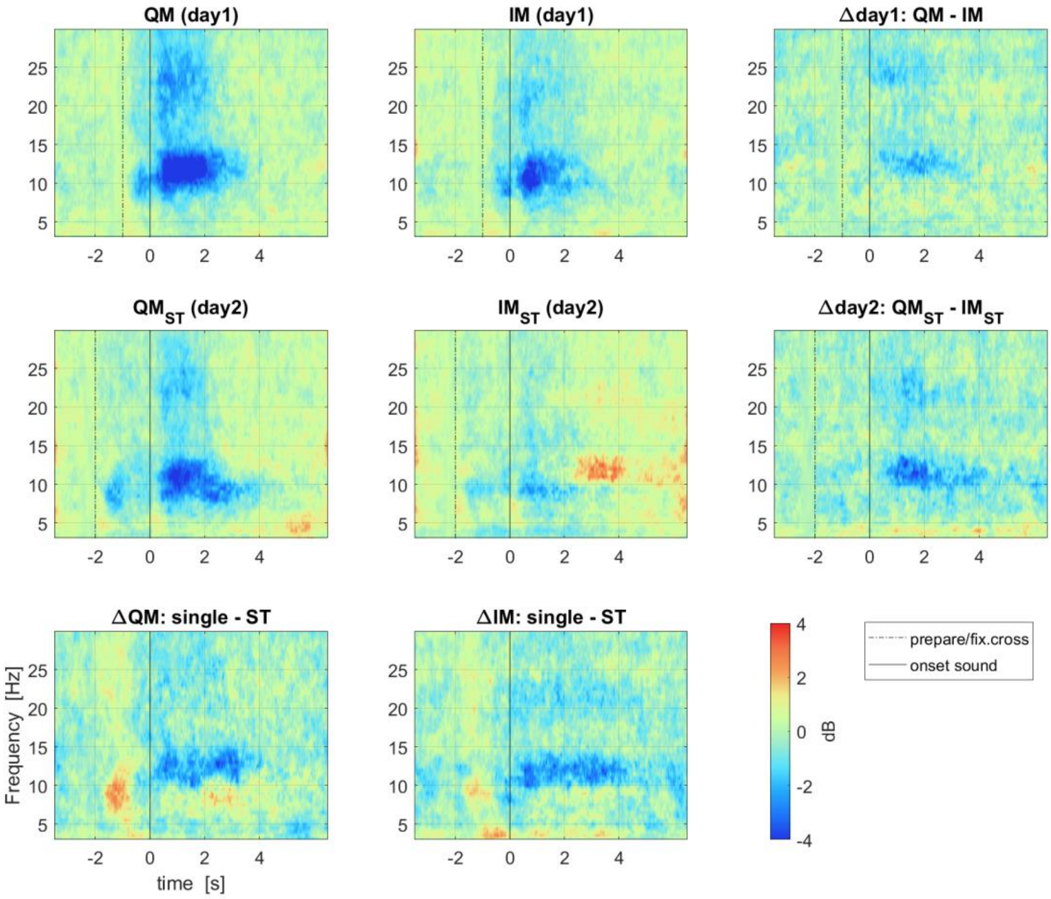

Figure 3. Group (N=11) median-averaged time-frequency plots per condition and differences between them. Individual data were computed for strongest individual CSP-derived contralateral sources for EEG alpha frequency band (see [24] for the details of the analysis).

CONCLUSION

We proposed a hypothesis that attempted movements can be more compatible with the interaction with the external world than imaginary movements, the mental task commonly used in noninvasive BCIs. Preliminary results of its testing using prosaccades as an example of external task and quasi-movements as a model of attempted movements were mostly in line with its predictions, suggesting that attempted movements should be probably considered at least as an important supplement of imagery in BCIs. More studies, however, are needed for more definite conclusions. The study also may be considered as a new demonstration of the potential of quasi-movements, a very little explored phenomenon, for BCI research.

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