

## SENSORIMOTOR RHYTHM DESYNCHRONIZATION DURING EXECUTION OF QUASI-MOVEMENTS BASED ON NATURAL FINGER MOVEMENTS

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Quasi-movements (QMs), which are movement attempts minimized to the point of movement extinction, evoke EEG patterns similar to those of real movement. QMs can model attempted movement in healthy subjects and are therefore of interest as an alternative to motor imagery (MI) in rehabilitation brain-computer interfaces (BCIs), in which the attempted movement of the paralyzed limb is used as a control signal. Earlier QM studies were focused on thumb abduction. The study aimed to verify the feasibility of QMs based on more natural actions (pressing and pointing) and compare their EEG correlates with those of MI. In 11 healthy volunteers (6 women, aged 21–32), EEG recording was performed during execution of MI, non-goal-directed QMs (nQMs), goal-directed QMs (gQMs), and real movements. Both QM types caused more pronounced contralateral desynchronization of the 8–13 Hz mu rhythm than MI (0.63 dB, effect of movement type,  $p = 0.042$ ), while nQMs and gQMs did not differ. There were no differences in ipsilateral desynchronization between the conditions ( $p = 0.216$ ). Pairwise comparisons were significant in the upper-frequency mu rhythm sub-range (nQM–MI: 0.82 dB,  $p = 0.003$ ; gQM–MI: 0.70 dB,  $p = 0.022$ ). There was no effect of movement type in the parietal area of interest ( $p = 0.15$ ). The contribution of residual movement was non-significant. The data obtained show that QMs based on natural actions are feasible and produce stronger sensorimotor activation than MI, which justifies further research focused on QMs in the context of rehabilitation BCIs.

**Keywords:** quasi-movements, motor imagery, attempted movement, mu rhythm desynchronization, electroencephalography, brain-computer interface, neurorehabilitation

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## ДЕСИНХРОНИЗАЦИЯ СЕНСОМОТОРНЫХ РИТМОВ ПРИ СОВЕРШЕНИИ КВАЗИДВИЖЕНИЙ, ОСНОВАННЫХ НА ЕСТЕСТВЕННЫХ ДВИЖЕНИЯХ ПАЛЬЦЕВ РУКИ

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Квазидвижения (КД) — попытки движения, минимизированные до исчезновения движения, — вызывают ЭЭГ-паттерны, схожие с реальным движением. КД могут моделировать попытки движения у здоровых участников и потому представляют интерес как альтернатива представлению движений (ПД) для реабилитационных интерфейсов мозг-компьютер (ИМК), в которых попытка движения парализованной конечностью используется как управляющий сигнал. КД ранее исследовали на отведении большого пальца. Целью данной работы было проверить осуществимость КД на основе более естественных действий (нажатие и указание) и сравнить их ЭЭГ-корреляты с ПД. У 11 здоровых добровольцев (6 женщин, возраст 21–32 года) регистрировали ЭЭГ при выполнении ПД, нецеленаправленных КД (нКД), целенаправленных КД (цКД) и реальных движений. Оба типа КД вызывали более выраженную контралатеральную десинхронизацию  $\mu$ -ритма 8–13 Гц, чем ПД (0,63 дБ, эффект типа движения,  $p = 0,042$ ), тогда как нКД и цКД не различались. Ипсилатеральная десинхронизация не различалась между условиями ( $p = 0,216$ ). В поддиапазоне верхнего  $\mu$ -ритма (10–13 Гц) попарные сравнения достигали значимости (нКД–ПД: 0,82 дБ,  $p = 0,003$ ; цКД–ПД: 0,70 дБ,  $p = 0,022$ ). В теменной области интереса эффект типа движения отсутствовал ( $p = 0,15$ ). Вклад остаточного движения не был значим. Полученные данные показывают, что КД на основе естественных действий осуществимы и обеспечивают более выраженную сенсомоторную активацию, чем ПД, что обосновывает их дальнейшее изучение в контексте реабилитационных ИМК.

**Ключевые слова:** квазидвижения, представление движений, попытка движения, десинхронизация  $\mu$ -ритма, электроэнцефалография, интерфейс мозг-компьютер, нейрореабилитация

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Kinesthetic motor imagery (MI) represents one of the operation strategies widely used in brain–computer interfaces (BCIs) [1]. However, MI is an inner-directed task that can compete with visual attention [2, 3] and external information processing [4], including the interface feedback. Furthermore, MI requires the user to perform an abstract mental task distinct from the real action [5, 6]. This motivates the search for alternative motor tasks, which would preserve informative EEG correlates and at the same time be closer to natural action.

A promising candidate for such a task is the quasi-movement (QM): a conscious reduction of movement amplitude to the point where both overt movement and muscle activation disappear [7], while the EEG patterns typical of real movement (RM) are preserved [7, 8]. Despite the fact that residual muscle activation can be preserved in a number of cases, recent reports suggest that the presence of such activation does not explain the QM-related EEG effects [9]. QMs are subjectively perceived as more similar to RM compared to MI, which may support the sense of control when using BCIs [10]. QMs were also proposed as a model of the attempted movement [11] previously discussed as a promising alternative to MI for BCIs, especially in clinical and rehabilitation applications [12, 13]. Thus, QMs can be also of interest as a method to study the attempted movement-like state in healthy subjects under controlled conditions.

However, today the studies of QMs remain largely limited to one movement: thumb abduction [7, 9], which was initially selected by the researchers due to ease of surface electromyography (sEMG) recording for appropriate muscles. This leaves open the question of whether QMs can be extended to more natural actions.

The possibility of executing goal-directed QMs is also of interest. Goal-directed actions are oriented towards objects of the external world or results. It has been shown that preparation for the goal-directed “reaching” movement is associated with the earlier and more widespread cortical activation than preparation for non-goal-directed movements, including more pronounced involvement of the parietal areas [14, 15]. Moreover, functional dissociations between the lower-frequency (8–10 Hz) and upper-frequency (10–12 Hz) mu rhythms have been reported: the upper-frequency component shows a more somatotopic pattern of desynchronization [16], while parietal alpha desynchronization reported during planning such movements is specifically associated with the goal-directed nature of movement [17]. These data suggest the possibility that EEG correlates of goal direction may be reflected by the amplitude of desynchronization over sensorimotor zones, as well as by involvement of parietal areas and dynamic changes in the upper-frequency mu rhythm. The question whether such effect can be observed during QMs when there is no apparent movement by definition, remains open.

The study aimed to test whether goal-directed hand movements can be realized as QMs and whether these preserve modulation of the sensorimotor rhythm making QMs promising for BCI applications. Additional tasks were to compare EEG correlates of new QMs with the kinesthetic MI of the same actions and to determine whether the effect of the goal-directed instruction is manifested in the sensorimotor or parietal area, as expected in the literature about the goal-directed movement planning [14, 17].

## METHODS

The study was conducted at the Moscow State University of Psychology & Education. A total of 11 healthy volunteers took part in the study (6 women aged 21–32 years, median age

28 years). Inclusion criteria: male or female healthy volunteers aged 18–35 years. Exclusion criteria: inability to move the arm, diagnosed neurological and/or mental disorders, episodes of seizure or diagnosed status epilepticus.

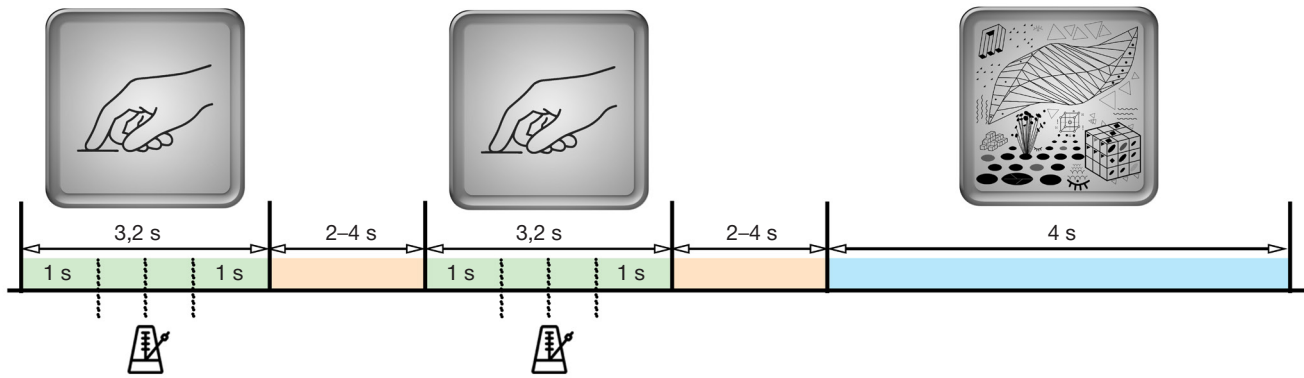
Signals were recorded using the Resonance platform [18]. EEG was recorded using the 10–10 system of 64 electrodes with the sampling frequency of 1000 Hz and the NVX136DC amplifier (Medical Computer Systems, Russia). The ground electrode was in Fpz. The electrode impedance below 20 kOhm was maintained.

A specialized strain gauge-based sensor was developed for mechanical recording of residual movement (hereinafter the strain gauge described in more detail in Appendix). The gauge was installed in the casing allowing the subject to place his/her hand palm down in a natural, relaxed position, with the distal phalanx of the index finger resting on the round plate (20 mm in diameter) flush with the surrounding surface. The gauge could detect slightest changes in the force applied by the finger, regardless of the direction. Surface EMG was considered unsuitable, since pressing and pointing depended on deep groups of muscles, and minimal residual activation during QMs would be difficult to interpret based on the surface electrode readings.

The subject sat in a chair in front of the computer screen. The right hand was placed palm down on the strain gauge with the index finger resting on the sensing plate. The sequence of stimulus presentation was delivered using the specially developed PyGame framework-based script [19]. Stimuli were presented in blocks; each block consisted of two motor sequences and one visual control sequence; intervals between sequences varied randomly from 2 to 4 s (Fig. 1). In each motor sequence, the image of the right hand executing an appropriate action (“pressing” or “pointing”) was presented at 3.2 s. Within 1 s after the beginning of image presentation, three short sound clicks were presented with a 600 ms inter-stimulus interval. The subject performed one repeat of the action appropriate under current condition in response to each click. In the visual sequence, an image with complex geometric elements was demonstrated for 4 s, and the subject counted elements of the selected type in his/her head at a comfortable pace, as previously reported [9]. Each condition included 20 blocks, a total of 40 motor and 20 visual sequences; the subjects went through 5–10 training blocks prior to each condition.

Movements of four types were recorded for each of two actions: real movement (RM), kinesthetic motor imagery (MI), non-goal-directed quasi-movement (nQM), and goal-directed quasi-movement (gQM). The RM condition was always executed the first, MI and nQM were presented randomly, and gQM was always executed the last for the movement. Such an order of presentation was selected due to the fact that goal direction was introduced by instructions, and the earlier gQM presentation could prematurely introduce the association of movement with its goal-directed nature. Therefore, before the gQM condition the researcher avoided such goal-directed action-related keywords, as “press”, “button”, or “point”, describing movement only in terms of motion in the joints. The same movement was presented again in the clearly goal-directed terms immediately before the gQM.

The QM training was adapted from previous studies [7, 9]. First, the strain gauge input signal was demonstrated to the subjects. They could make sure that it changed when moving the index finger. To emphasize signal changes, the sum of absolute differences between the current and delayed signal was displayed, which made it possible to clearly identify changes in pressure on the gauge [20]. After the gauge signal



**Fig. 1.** Stimulus presentation block structure. Each block consisted of two 3.2 s motor sequences (green), in each of which three sound signals were presented with an interval of 600 ms (vertical dotted lines). At the end of the block, a visual task was presented for 4 s (blue); the intervals between motor sequences and the visual task (yellow) varied randomly from 2 to 4 s. Images (above) are given as an example of stimuli displayed on the screen

amplitude decreased to the slightly elevated noise level, the subject continued to reproduce the movement in response to individual sound signals without any visual control; when the researcher noted the residual signal, the subject was further instructed to minimize the amplitude. After the stable QM execution was achieved, the researcher asked control questions in order to confirm the fact that the subject did not turn to motor imagery or any other unintended movement. Finally, the subjects practiced responding to triplets of sound signals used in the basic experiment.

The QM training was conducted immediately prior to the corresponding conditions using the standard kinesthetic imagery procedure [7, 9]: the subject executed the movement with the full amplitude, described the emerging kinesthetic sensations (tension, gravity, stretching, warmth), and then used these as a basis for imagery. The training continued until the task was confidently performed at the required pace.

Processing was performed in MNE-Python. EEG channels showing signs of high noise levels, abnormal amplitude, or poor electrode contact with the scalp skin were detected automatically using PyPREP [21, 22], then these were interpolated; after that the data were transformed into a Laplacian montage [23, 24]. Residual movement was quantified based on the strain gauge signal using the robust peak amplitude (RPA) determined as the difference between the 95th and 5th percentiles within each epoch. This measure was selected as the one less influenced by single artifacts compared to the difference of the minimum and maximum values upon detection of the slightest and irregular residual movements during QMs.

EEG analysis was performed using the sensorimotor region of interest (ROI) including electrodes FC5, FC3, C3, C1, CP3, CP1 and FC6, FC4, C4, C2, CP4, CP2. Power within single epochs was calculated by the Morlet wavelet transform method for each channel in the ROI and normalized to the baseline level in dB as

$$10 \log_{10}(\text{Power} / \text{PresLevel}),$$

where PresLevel — average power within an interval (–1.5...–0.5 s) until the first sound signal. Desynchronization in the

sensorimotor ( $\mu$ ) range (8–13 Hz) (hereinafter event-related desynchronization, ERD) was determined by averaging in a window (0.07... 1.5 s) relative to the first sound signal. The electrode showing the maximum effect within the ROI was selected for analysis for each subject and condition, as previously reported [7].

To test whether goal direction could be manifested by specific frequency or spatial patterns not detected during the basic analysis, two secondary analyses were conducted. First, ERD in the upper-frequency mu rhythm sub-range (10–13 Hz) was estimated for the same sensorimotor ROI. Second, the parietal ROI including electrodes P3, P1, CP3 was determined, where the full-range (8–13 Hz) analysis was conducted. Both secondary analyses involved the use of the same time/frequency decomposition, baseline normalization, and electrode selection procedures, as the basic analysis.

Statistical analysis was conducted in R using lmerTest and emmeans for post-hoc comparison. Mu ERD was analyzed using linear mixed effects models (1):

$$\text{ERD} \sim \text{Action} + \text{RPA} \times \text{MovementType} + \text{PrecTask} + \text{PresLevel} + (1 + \text{Action} / \text{Subject}) \quad (1)$$

Variables are described in Table 1. Random effects included random intercepts and random slopes for the Action factors by subjects, which allowed us to consider individual variability of both overall ERD level and differences between the “pressing” and “pointing” conditions. The interaction between RPA and movement type was included to assess the contribution of residual muscle activity for each particular movement type. Continuous predictors were normalized (z-transform); RPA was standardized within each level of the Action factor. The linear mixed effects models used due to the repeated intra-subject data structure allowed us to consider the intra-subject dependence of observations. Significance of fixed effects was assessed using type III F-tests (lmerTest::anova) with the Satterthwaite approximation for degrees of freedom, where

**Table 1.** Independent variables used in linear mixed effects models. MI — motor imagery, nQMs — non-goal-directed quasi-movements, gQMs — goal-directed quasi-movements

| Variable     | Description                | Values                 |
|--------------|----------------------------|------------------------|
| Action       | action                     | "pressing", "pointing" |
| RPA          | robust peak amplitude      | continuous             |
| MovementType | movement type              | MI, nQMs, gQMs         |
| PrecTask     | task in the preceding test | motor, visual          |
| PresLevel    | pre-stimulus power level   | continuous             |
| Subject      | subject ID                 | "1", "2"... "11"       |

**Table 2.** Average group proportion of epochs with the increased residual movement under the QM conditions: nQMs — non-goal-directed quasi-movements, gQMs — goal-directed quasi-movements

|      | "Pressing" | "Pointing" |
|------|------------|------------|
| nQMs | 36.75%     | 44.25%     |
| gQMs | 45.60%     | 37.80%     |

F-values were obtained from the same linear model, not from any separate analysis of variance based on average data. The post-hoc comparison of the MovementType factor levels was performed using estimated marginal means (emmeans) with Tukey adjustment for multiple comparisons.

Secondary analyses (upper-frequency mu sub-range and parietal ROI) were conducted using a simplified model (2), from which RPA and its interaction with movement type were excluded (the basic analysis showed that these were non-significant), and the random structure was limited to the random intercept in order to ensure stability of estimation with a weak signal.

$ERD \sim Action + MovementType + PrecTask + PresLevel + (1 / Subject) (2)$

A model (3) constructed separately for the "pressing" and "pointing" conditions was used to analyze the differences in RPA between all conditions; there was no RPA normalization.

$RPA \sim MovementType + (1 / Subject) (3)$

The secondary analysis of the data subset including the RM, nQM, and gQM conditions was used to directly compare QMs and RMs. A simplified model (4), from which the RPA predictor was excluded, was used, since the analysis showed that the RPA was 1–2 orders higher during RM than QM, and this difference represented an intrinsic difference between the conditions, not a confounder. We also added the Action  $\times$  MovementType interaction to assess possible differences in movement type effect between "pressing" and "pointing".

$ERD \sim Action \times MovementType + PrecTask + PresLevel + (1 + Action / Subject) (4)$

The post-hoc comparison of MovementType levels was performed separately within each Action level using emmeans and Tukey adjustment.

## RESULTS

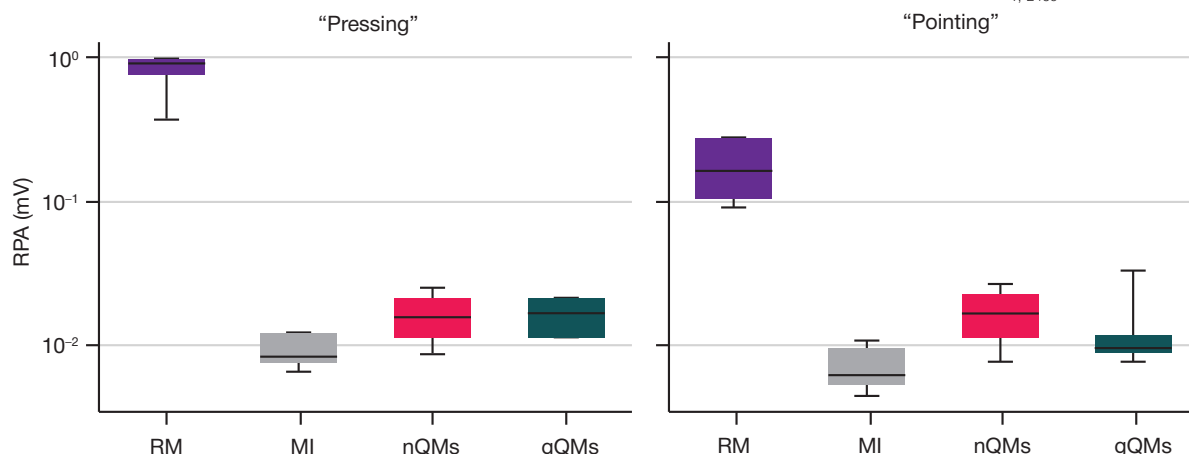
The subjects differed considerably in the percentage of trials without increased residual movement under the QM conditions, which was defined as the RPA exceeding the 97.5<sup>th</sup> percentile of the RPA observed within the MI condition for a given subject. The average group proportions of epochs with the increased residual movement are provided in Table 2. Nevertheless, none of the subjects showed RPA under the QM conditions higher than the minimal RPA observed during RM (Fig. 2).

Type III F-tests for the model (3) showed that there were significant differences in RPA between the conditions for both actions ("pressing":  $F_{3, 29} = 117.55, p < 0.001$ ; "pointing":  $F_{3, 29} = 16.28, p < 0.001$ ). The post-hoc comparison revealed the same pattern for both actions: RPA was significantly higher during RM than MI, nQM, and gQM (all  $p < 0.001$ ), while implicit conditions did not differ (all  $p > 0.97$ ). The full model inference is provided in Appendix (Table A1).

Since the main goal of the study was to compare new QMs with the corresponding MIs, the RM condition was excluded from the ERD analysis. The contralateral mu ERD analysis (Fig. 3, 4) involving the use of linear mixed effects models revealed significant effects of the action ( $F_{1, 10.4} = 7.76, p = 0.019$ ), movement type ( $F_{2, 2423} = 3.17, p = 0.042$ ), preceding task ( $F_{1, 2410} = 26.85, p < 0.001$ ), and pre-stimulus amplitude ( $F_{1, 2416} = 23.84, p < 0.001$ ). In contrast, neither RPA, nor its interaction with movement type was significant ( $F_{1, 2381} = 0.001, p = 0.973$  and  $F_{2, 2398} = 0.33, p = 0.722$ , respectively). The full model inference is provided in Table 3.

The contralateral mu ERD reported for "pressing" was more pronounced than that reported for "pointing". Both QM conditions were associated with the more pronounced ERD than MI. The post-hoc comparison showed the MI–nQM difference of borderline significance (0.63 dB,  $p = 0.050$ ), and the MI–gQM difference was non-significant ( $p = 0.073$ ); there was no difference between the nQM and gQM ( $p > 0.999$ ).

As for ipsilateral mu ERD, the analysis revealed significant effects of the preceding task ( $F_{1, 2409} = 54.33, p < 0.001$ ) and

**Fig. 2.** Robust peak amplitude (RPA) of the strain gauge signal for various movement types and actions. Box plots show median values and interquartile ranges, whiskers — range from minimum to maximum. Ordinate axis — log scale. RM — real movement, MI — motor imagery, nQMs — non-goal-directed quasi-movements, gQMs — goal-directed quasi-movements

**Table 3.** Full inference of the mixed effects model (1) for the contralateral mu ERD. The table provides coefficients of the model fixed effects; p-values for post-hoc comparisons with Tukey adjustment are provided in the text

| Effect                     | $\beta$ | SE   | df   | $t$    | $p$     |
|----------------------------|---------|------|------|--------|---------|
| Intercept                  | -10.92  | 0.54 | 14.1 | -20.27 | < 0.001 |
| Action (pointing–pressing) | 0.67    | 0.24 | 10.4 | 2.79   | 0.019   |
| RPA                        | 0.07    | 0.38 | 2414 | 0.17   | 0.862   |
| MovementType (nQM–MI)      | -0.64   | 0.27 | 2423 | -2.35  | 0.019   |
| MovementType (gQM–MI)      | -0.63   | 0.29 | 2428 | -2.19  | 0.028   |
| PrecTask (motor–visual)    | 0.96    | 0.19 | 2410 | 5.18   | < 0.001 |
| PresLevel                  | -0.46   | 0.09 | 2416 | -4.88  | < 0.001 |
| RPA × MovementType (nQM)   | -0.01   | 0.40 | 2416 | -0.02  | 0.983   |
| RPA × MovementType (gQM)   | -0.17   | 0.42 | 2420 | -0.42  | 0.675   |

pre-stimulus amplitude ( $F_{1, 2419} = 9.83, p = 0.002$ ). In contrast, effects of the action ( $F_{1, 9.6} = 0.25, p = 0.632$ ), movement type ( $F_{2, 2423} = 1.53, p = 0.216$ ), RPA ( $F_{1, 2402} = 0.56, p = 0.456$ ), and interaction between the RPA and movement type ( $F_{2, 2413} = 0.29, p = 0.748$ ) were non-significant. None of pairwise comparisons between movement types was significant ( $p = 0.686$  for MI–nQM,  $p = 0.782$  for MI–gQM, and  $p = 0.191$  for nQM–gQM). For full model inference see Table A2.

The secondary analysis of the contralateral ERD in the upper-frequency mu rhythm sub-range (10–13 Hz) revealed significant effects of the action ( $F_{1, 2424} = 12.29, p < 0.001$ ), movement type ( $F_{2, 2428} = 6.33, p = 0.002$ ), preceding task ( $F_{1, 2422} = 14.98, p < 0.001$ ), and pre-stimulus level ( $F_{1, 2426} = 71.27, p < 0.001$ ). As in the basic analysis, the upper-frequency mu rhythm ERD reported for “pressing” was more pronounced than that reported for “pointing”. The post-hoc comparison confirmed that the ERD was significantly stronger during nQM compared to MI (0.82 dB,  $p = 0.003$ ) and gQM compared to MI (0.70 dB,  $p = 0.022$ ), while nQM and gQM did not differ (0.12 dB,  $p = 0.89$ ). For full model inference see Table A3.

The pattern in the parietal ROI was significantly different. Significant effects were reported for the preceding task ( $F_{1, 2422} = 26.36, p < 0.001$ ) and pre-stimulus level ( $F_{1, 2424} = 49.47, p < 0.001$ ). In contrast, effects of the action ( $F_{1, 2424} = 2.82, p = 0.093$ ) and movement type ( $F_{2, 2427} = 1.90, p = 0.15$ ) were non-significant. None of pairwise comparisons between movement types was significant (MI–nQM: 0.45 dB,  $p = 0.13$ ; MI–gQM: 0.28 dB,  $p = 0.49$ ; nQM–gQM: 0.17 dB,  $p = 0.78$ ). For full model inference see Table A4.

The direct comparison of QMs with RMs in the contralateral sensorimotor ROI revealed a significant interaction between the action and movement type ( $F_{2, 2388} = 3.42, p = 0.033$ ) suggesting a different nature of the effects for the two actions. As for “pressing”, both QM conditions were associated with the significantly more pronounced mu ERD compared to the RM: the differences were 0.98 dB for nQM ( $p = 0.003$ ) and 1.18 dB for gQM ( $p < 0.001$ ); there were no differences between nQM and gQM (0.20 dB,  $p = 0.82$ ). As for “pointing”, none of pairwise comparisons was significant (RM–nQM: 0.21 dB,  $p = 0.76$ ; RM–gQM: 0.04 dB,  $p = 0.99$ ; nQM–gQM: -0.17 dB,  $p = 0.86$ ). The full model inference is provided in Table A5.

## DISCUSSION

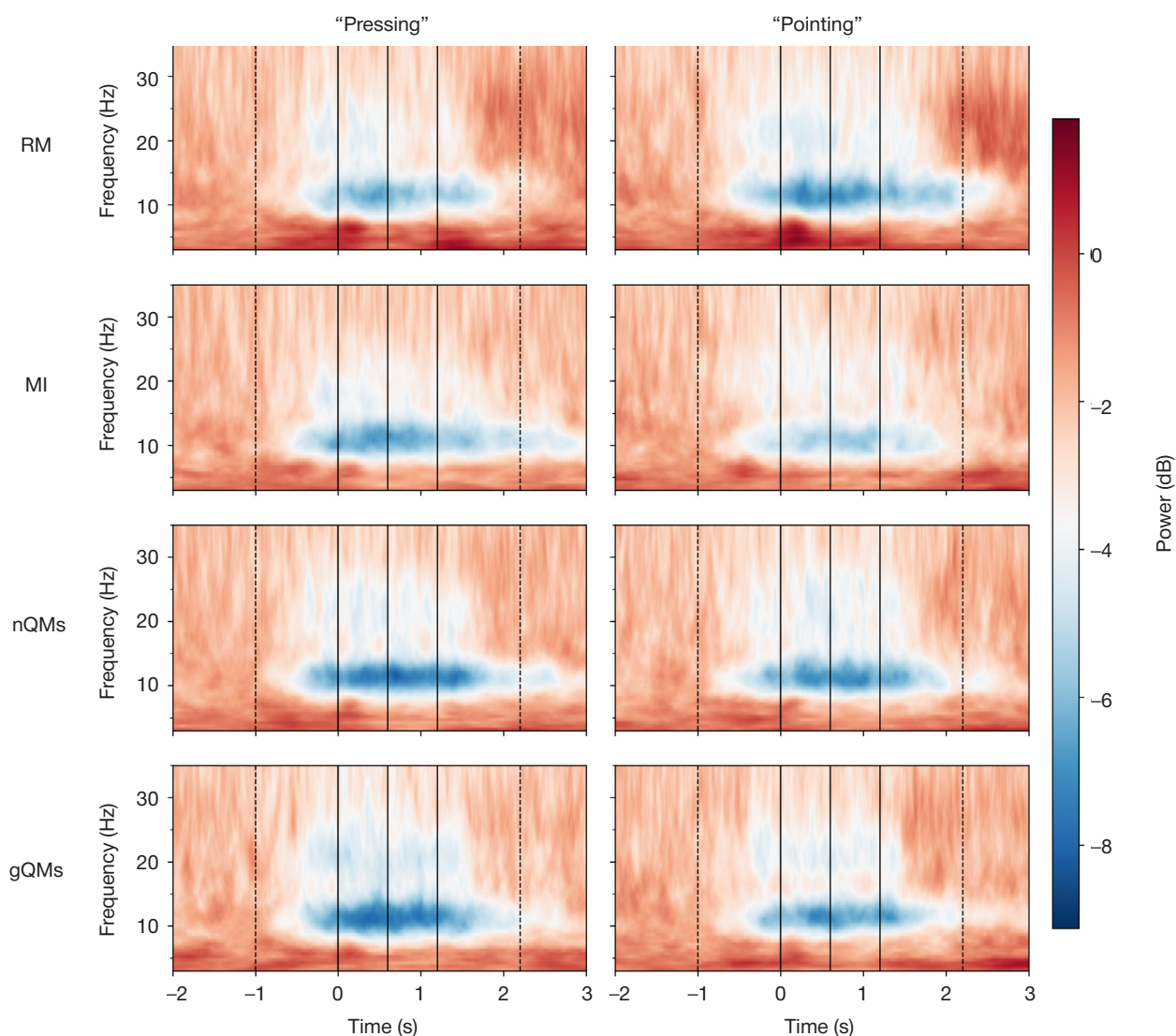
The experimental results presented above should be considered preliminary due to the limited number of subjects, despite the fact that the study was based on the previously determined effect [7, 9] and focused on testing the effect generalizability instead of initial detection. Considering these limitations, the

data obtained suggest that QMs can be extended beyond the “classic” thumb abduction paradigm [7] to more natural actions of the hand, such as pressing and pointing with the index finger. The main finding was that both QM conditions demonstrated more pronounced contralateral mu ERD compared to MI, while there were no significant differences in the ipsilateral mu ERD between the conditions. The effect direction and size (about 0.63 dB) were uniform for both QM types, and both comparisons were significant when performing secondary analysis of the upper-frequency mu sub-range (10–13 Hz). The residual movement contribution quantified using the RPA was significant in neither cerebral hemisphere. In general, this pattern suggests that superiority of new QMs over imagery manifested itself mainly in the contralateral sensorimotor activation and could hardly be explained by residual muscle activation.

In this regard, these results are generally consistent with the original study of QMs, in which alpha ERD decreased in the order RM > QM > MI, especially in the contralateral hemisphere [7]; the findings are also consistent with the later analysis showing that the more pronounced contralateral ERD during QM compared to MI could not be explained by residual muscle activity only [9]. Thus, the data obtained complement the earlier information about QMs, suggesting that superiority over imagery can be achieved for the hand movements more natural than thumb abduction.

The lack of additional effects of the goal-directed instruction deserves in-depth consideration. The available data suggest that the goal direction may be expressed not so much in the increased average ERD over the central sensorimotor areas, as in a wider spatial distribution and more pronounced involvement of the parietal areas, especially in the upper-frequency alpha range [14–17, 25]. To test this option, secondary analyses were conducted in the upper-frequency mu sub-range (10–13 Hz) and parietal ROI. When analyzing the upper-frequency mu rhythm, both QM conditions showed more pronounced ERD compared to MI again, but there were no differences between nQMs and gQMs. The parietal area analysis revealed a non-significant overall effect of movement type, and the nQM–gQM contrast was also lacking.

There can be several explanations of such findings. First, both actions used per se are highly familiar and naturally associated with objects of the external world and results. Even the nominally non-goal-directed variants could partially preserve the usual meaning of the action, making the contrast between nQMs and gQMs less sharp. Second, the gQM condition was presented the last for each movement in order to avoid contamination of neutral conditions, which was methodologically substantiated, but could limit the possibility

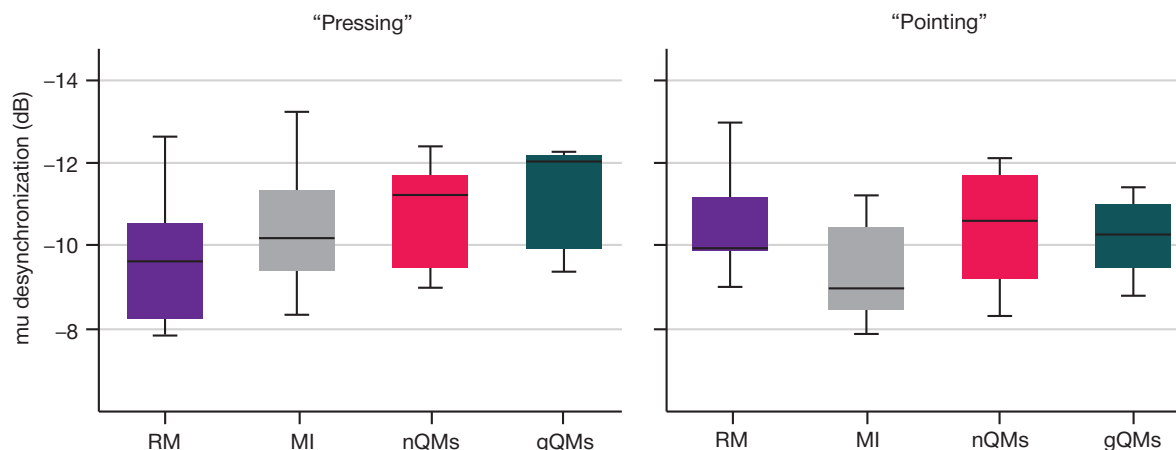


**Fig. 3.** Average group time-frequency spectrograms of EEG power (Morlet wavelet transform) in the contralateral sensorimotor region of interest for various actions and movement types. Power is normalized to the baseline level in dB; blue color corresponds to desynchronization, red — synchronization. Vertical dotted lines show the time range of visual stimulus presentation. Vertical solid lines correspond to the time of presenting three sound signals. RM — real movement, MI — motor imagery, nQMs — non-goal-directed quasi-movements, gQMs — goal-directed quasi-movements

of extracting the pure goal direction effect. Third, probably most important is that manipulation of goal direction in this study was purely instructional: the subjects were asked to conceive movement in terms of goal direction. In contrast, the studies that revealed effects of goal direction in the parietal areas and upper-frequency mu range used real reaching for visible objects [14, 15, 17], and the goal was set perceptually. Perhaps, instructional framing alone is not sufficient to engage the parietal planning network that provides the distinction between goal-directed and non-goal-directed actions at the cortical level.

Neither the main RPA effect, nor its interaction with movement type was significant in the mu ERD analysis, and residual movement during QMs was statistically indistinguishable from that observed during MI. This is evidence against the simplest explanation: that the more pronounced ERD during QMs simply reflected residual movement. Our results support the hypothesis that QMs represent a distinct motor skill-associated state, which is closer to overt movement than imagery, at the cortical level, but remains implicit in terms of behavior [9]. The strain gauge directional sensitivity was not calibrated separately, but the lack of dissociation between pressing and pointing under implicit conditions represents evidence against this limitation as a source of the effects observed.

The direct comparison of QMs with RM revealed a differentiated pattern. As for “pressing”, both QM types were associated with the significantly higher contralateral mu ERD than real movement, while RM, nQMs, and gQMs yielded comparable desynchronization for “pointing”. Superiority of the ERD associated with “pointing” under the QM conditions over that associated with RM, at first glance incompatible with the results of the study [7], can be explained within the framework of the neural efficiency concept: the highly familiar automated movements may be associated with the reduced sensorimotor ERD [26–29], while QMs require the more resource-consuming control, since it is necessary to generate a motor command and suppress explicit execution of the command at the same time [7, 30], in contrast to MI, during which inhibition of movement is automatic [30]. “Pressing” is the action repeatedly automated in everyday life, and it was for pressing that neural efficiency could clearly emerge. “Pointing” was likely to be less automated than “pressing”, contrary to the initial hypothesis about comparable familiarity of both actions, and no reported dissociation between RM and QMs was observed for pointing. This is consistent with the interpretation that the observed QM superiority over RM during “pressing” is associated specifically with the automatic



**Fig. 4.** Contralateral mu ERD (8–13 Hz) for various actions and movement types. More negative values correspond to stronger ERD. Box plots show median values and interquartile ranges by subjects; whiskers — range from minimum to maximum. RM — real movement, MI — motor imagery, nQMs — non-goal-directed quasi-movements, gQMs — goal-directed quasi-movements

nature of real movement, not with the general properties of quasi-movements as a class of tasks.

In terms of being used in BCIs, the more pronounced contralateral mu ERD observed during QMs compared to MI, most clearly in the upper-frequency mu rhythm sub-range, is consistent with the general idea that the motor skill-related states closer to real movement can provide more informative control signals than classic imagery itself [1]. Thus, our study supports further development of QMs based on natural actions as a useful intermediate model between imagery and overt movement, and particularly as a model involving healthy volunteers for attempted movement-based BCIs [7, 11]. Therefore, further research should involve replication in a larger sample, more explicit manipulation of the action goal direction and testing of such new QMs in the BCI online paradigms.

## CONCLUSIONS

It has been shown that QMs can be successfully realized based on both thumb abduction and more natural actions of the hand: pressing and pointing. Both QM types caused stronger activation of the contralateral sensorimotor cortex compared to kinesthetic imagery of the same actions. This effect, which was especially clear in the upper-frequency mu rhythm sub-range (10–13 Hz), could not be explained by residual movement. The instruction introducing goal direction did not enhance desynchronization in the sensorimotor or parietal area. The findings suggest that QMs based on natural actions are promising for rehabilitation brain–computer interfaces as an alternative to motor imagery.

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