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Combining Virtual Reality Feedback and Transcranial Alternating Current Stimulation to Enhance Restorative Brain-Computer Interfaces

Joana Saraiva[1,2], Daniela Esteves[3], Christel Bour[4], Sofia Fernandes[1,2]‡, Athanasios Vourvopoulos[3]‡

[1]Department of Physics, Faculdade de Ciências, Universidade de Lisboa, Lisbon, Portugal
[2]Instituto de Biofísica e Engenharia Biomédica, Faculdade de Ciências, Universidade de Lisboa, Lisbon, Portugal
[3]Institute for Systems and Robotics (ISR-Lisboa), Department of Bioengineering, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
[4]Grenoble INP-UGA (Grenoble Institute of Technology - Grenoble Alpes University), Grenoble, France
‡These authors contributed equally to this work and are joint senior authors.

E-mail: fc58701@alunos.ciencias.ulisboa.pt

ABSTRACT: In stroke rehabilitation, brain–computer interfaces (BCIs) enable neurofeedback-based regulation of sensorimotor rhythms, promoting motor-related cortical reorganization. Integrating virtual reality (VR) into BCI paradigms enhances this process through immersive, multisensory feedback that strengthens sensorimotor engagement. In parallel, transcranial alternating current stimulation (tACS) may further modulate motor imagery(MI)–related oscillatory activity. Together, these approaches offer a multimodal framework to optimize neurorehabilitation outcomes. This study investigated the synergistic effects of a MI-based VR-BCI paradigm and tACS applied at the individual alpha frequency (IAF). Twelve healthy participants performed bimanual MI tasks in VR and non-VR conditions before and after sham or active tACS. Alpha event-related desynchronization (ERD) served as the primary outcome. VR elicited stronger contralateral and more widespread ERD, including parietal and occipital regions. tACS effects were subtle and, in VR, sometimes attenuated ERD.

INTRODUCTION

Neurological disorders rank as the primary driver of disability worldwide and frequently result in motor impairments that profoundly affect individuals' independence and quality of life. Since 1990, the burden of neurological disorders, measured in disability-adjusted life years (DALYs), has risen by 18% [1].

Conventional therapy strategies, such as physical therapy, often require residual voluntary motor function and frequent supervised sessions, which many severely impaired patients cannot achieve [2]. These limitations have motivated the development of neurotechnology-based interventions as complementary approaches that directly target the central nervous system.

Non-invasive Brain-computer interfaces (BCIs), which enable the control of external devices in real-time using neural activity, usually recorded through electroencephalography (EEG), allow users to control virtual reality (VR) avatars or robotic devices through motor imagery (MI), forming closed-loop systems that strengthen key motor pathways [3]. MI is the mental simulation of movement without muscle activation, engaging sensory and cognitive processes. Both MI and motor execution (ME) are known to induce event-related desynchronization (ERD), which is a reduction in EEG power in the alpha (8–12 Hz) and beta (12–30 Hz) bands, due to their desynchronization over sensorimotor areas [4]. This brain rhythm modulation that results from BCI training has shown to correlate with motor recovery [5, 6].

VR is increasingly integrated with BCIs to enhance embodiment and user engagement by delivering immersive, task-oriented feedback environments [7]. VR-BCI systems have been shown to strengthen cortical activation, with studies reporting robust contralateral event-related desynchronizations (ERDs) comparable to those observed during motor execution (ME) [8].

To further amplify these effects, VR-BCI training has been combined with non-invasive brain stimulation (NIBS). Repetitive transcranial magnetic stimulation (rTMS) enhances cortical excitability and strengthens ERD during VR-BCI training, though benefits appear to be short-term [6]. Transcranial electrical stimulation (tES) techniques, including transcranial direct current stimulation (tDCS) and transcranial alternating current stimulation (tACS), modulate neural activity using weak currents.

tDCS combined with VR feedback has yielded greater and clinically significant motor function improvements compared with conventional physical therapy [9]. Furthermore, MI-based VR-BCI paradigms coupled with tDCS have shown potential to modulate sensorimotor rhythms and support motor recovery, although existing evidence remains preliminary [10, 11]. Reported effects include modulations in alpha and beta rhythms and gains

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in motor performance. Nonetheless, these findings are tempered by important limitations, such as small sample sizes, lack of control conditions and the use of bilateral montages that may attenuate interhemispheric differences [10, 11]. Overall, the effectiveness of tDCS appears to depend strongly on stimulation parameters and spatial targeting, underscoring the need for more optimized and personalized approaches.

tACS is particularly suited for personalized stimulation, because it can target intrinsic oscillations such as the individual alpha frequency (IAF), defined as the frequency within the alpha band at which EEG power is maximized, and which is strongly correlated with task preparation and engagement [6, 12]. tACS has been shown to enhance MI performance and hybrid BCI classification (combining MI and steady-state visual evoked potentials) [13], suggesting a potential to amplify contralateral ERDs induced by VR-BCI.

Given the limited exploration of this combination, the present study proposes a hybrid approach integrating VR-BCI with tACS applied at the participants' IAF measured during resting-state EEG, aiming to determine whether this personalized stimulation enhances MI-related BCI features beyond VR-BCI alone, thereby supporting more effective neurorehabilitation.

MATERIALS AND METHODS

Participant recruitment: Twelve healthy, right-handed participants (six females; mean age 21.08 ± 1.16 years) were recruited. None had prior experience with BCI systems and three (S07, S10 and S12) had previously participated in non-invasive tES studies without adverse effects. Written informed consent was obtained in accordance with the 1964 Declaration of Helsinki. This study was approved by the Ethics Committee of Instituto Superior Técnico (CE-IST) with Ref. no. 22/2024.

EEG acquisition: EEG was recorded using a 32 active electrode's amplifier (Liveamp32, Brain Products GmbH, Gilching, Germany), positioned according to the international 10–20 system. Signals were acquired through the BrainVision Recorder at a sampling rate of 250 Hz, with electrode impedance maintained below 10 $k\Omega$ (Figure 1(A)(i)).

VR setup: The NeuRow environment [2] is a first-person perspective upper-limb MI training paradigm that renders two virtual hands performing left- and right-sided rowing movements [6, 7] (Figure 1(B)(ii)). The visual feedback for this study was presented on a computer screen.

Electric field (EF) modeling: EF simulations were performed using the example head model in *SimNIBS 4.1.0*, comprising six tissue compartments (scalp, skull, cortical gray matter (GM), cortical white matter (WM), cerebrospinal fluid (CSF) and eyes) represented by a finite element mesh with approximately 4.76×10^6 tetrahedral elements, with standard conductivity values provided by *SimNIBS* [14].

Table 1: Comparison of the EF magnitude (*magnE*) and focality between the ideal (**C3**, C1, C2 and **CP2**) and selected (**CP3**, C1, C2 and **CP4**) montages. Percentile values refer to the maximum EF intensity in the GM.

Montage	magnE (V/m)			Focality ($\times 10^4 mm^3$)	
	99.9%	99.0%	95.0%	75%	50%
Ideal	0.422	0.322	0.241	0.809	6.020
Selected	0.423	0.336	0.258	1.080	8.230
Δ (%)	0.237	4.348	7.054	33.498	36.711

Four circular electrodes (π cm^2) were modeled with a 1 mm electrode silicone rubber pad ($\sigma = 29.4$ S/m) and a 2.5 mm saline-soaked sponge layer ($\sigma = 1.0$ S/m). The maximum total injected current was set to 4 mA (maximum 1 mA per electrode), with up to four active electrodes.

The primary motor cortex (C3/C4) was defined as the stimulation target using the *SimNIBS* optimization script with coordinates expressed in Montreal Neurological Institute (MNI) space [15]. Since C3/C4 were required for EEG, the ideal montage (anodes: C1 and C3; cathodes: C2 and CP2) was adjusted by replacing C3 with CP3 and, for symmetry, CP2 with CP4, yielding, at targets, comparable EF magnitudes with some loss of focality (Table 1).

Given the low frequencies used in tACS, a quasi-static approximation was assumed, treating tissues as predominantly resistive and the EF as linearly proportional to the injected current. Session-specific EF magnitudes were thus estimated by scaling a reference EF of 0.256 V/m (obtained from *SimNIBS* simulations of the selected montage and defined as the mean within 15 mm radius spherical ROIs centered on left and right M1 [15]) according to the applied current (Table 3). Since EF magnitudes around 0.1–0.2 V/m are suggested to induce neuromodulatory effects [16], sessions reaching at least 0.1 V/m are highlighted.

tACS setup: tACS was delivered using the *StarStim* device (Neuroelectrics, Barcelona, Spain) with four channels (anodes - C1, CP3; cathodes - C2, CP4) through saline-soaked sponges (π cm^2). The reference was placed on the earlobe (Figure 1(A)(ii)).

Stimulation frequency was set to each participant's IAF, defined as the average IAF value from C3, Cz and C4 during the 2-minute eyes-open resting-state EEG, consistent with the task design. Intensity was determined through a threshold test starting at 300 μA and increasing in 100 μA steps until sensations were reported. The applied intensity corresponded to the level immediately below this threshold.

Protocol: Each session lasted approximately one hour and participants completed the VR and No VR sessions in randomized order, separated by at least 48 hours to ensure safety with tACS exposure.

Sessions began with a 4-minute resting-state EEG acquisition period to determine the participant's IAF, followed by the threshold test described in Section *tACS montage and setup*. Three MI tasks were performed per session, each with 40 randomized trials per side (left or right). Each trial comprised a 2-second baseline, 1-

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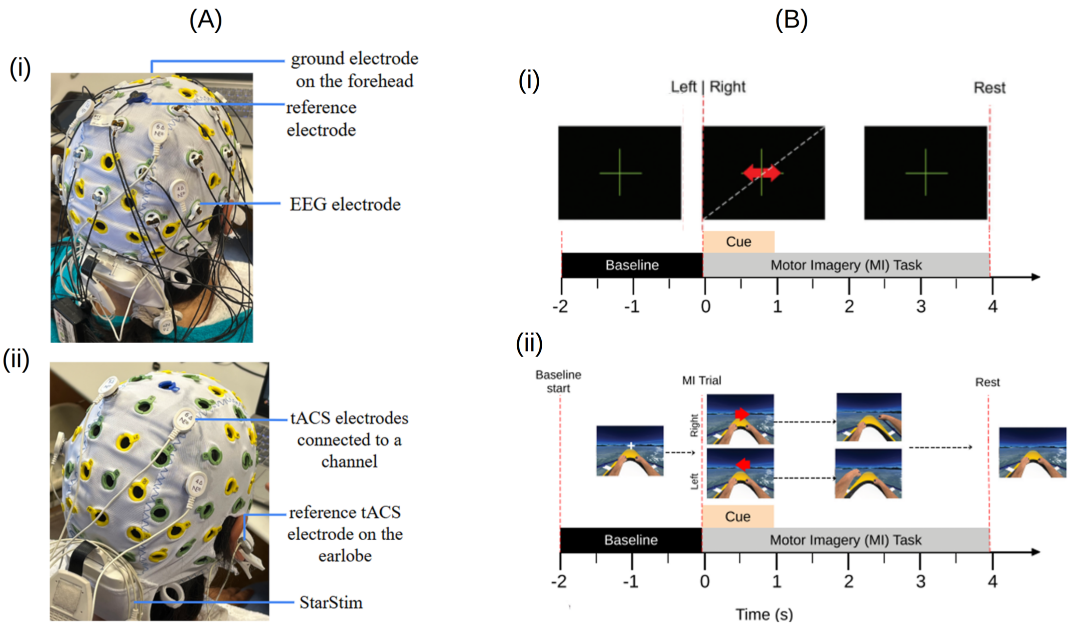

Figure 1: (A) Experimental setup illustrating (i) the EEG recording configuration with 32 active electrodes and (ii) the tACS setup. (B) Structure of each MI trial for tasks 1, 2 and 3: Each trial begins with a 2-second baseline, followed by a 1-second cue indicating left- or right-side MI, resulting in a 4-second MI trial. (i) No-VR condition, (ii) VR condition.

second cue and 4-second MI execution period, respectively (Figure 1(B)).

Task 1 served as training prior to any stimulation. Between tasks, participants received sham and active tACS for 15 minutes, with either eyes closed or fixated on a cross, in a blinded manner, such that Task 2 followed sham stimulation and Task 3 followed active tACS. Participants were informed they would undergo two stimulation periods without being told which was active tACS or sham. However, they were made aware of potential stimulation sensations, as this was necessary for the threshold test to determine whether they perceived it.

Participant questionnaires: Before data acquisition, participants completed an *Exclusion Criteria* questionnaire to screen for tACS contraindications [17] and the *Vividness of Movement Imagery* questionnaire (VMIQ), in a 7-point Likert scale, to assess their ability to generate vivid mental images during various MI tasks [18]. After each stimulation period, an *Adverse Effects* questionnaire was administered [19]. At the end of the VR session, an *Embodiment* questionnaire evaluated body ownership, self-location and agency [20].

Pre-processing: EEG data were pre-processed in MATLAB R2023b (The MathWorks, MA, United States) using EEGLAB v2025.0.0. Signals were downsampled to 128 Hz and band-pass filtered between 1–40 Hz. Independent Component Analysis (ICA) was applied to remove remaining artifactual components from the EEG data [7]. Components classified by *ICLabel* as 'Muscle' or 'Eye' with $\geq 90\%$ probability were rejected [7]. Next, visual inspection and the Artifact Subspace Reconstruction (ASR) method were used. Finally, data were re-referenced to the common average and epoched from -2 to +4 seconds around cue onset.

ERD power computation: The Event-Related Spectral Perturbation (ERSP) was estimated from the time and frequency domains using a 3-cycle Morlet wavelet with a Hanning taper. Values were expressed in decibels (dB) across 0.5 Hz bins relative to the mean baseline power and converted to alpha ERD using Equation 1.

$$ERD(\%) = (10^{\frac{ERSP_{dB}}{10}} - 1) \times 100 \quad (1)$$

Lateralization index (LI) calculation: LI was calculated from alpha-band ERD over electrodes C3 and C4, as shown in Equation 2 [7].

$$LI_{ERD} = \frac{(ERD_{C3(L)} - ERD_{C4(L)}) + (ERD_{C4(R)} - ERD_{C3(R)})}{2} \quad (2)$$

A positive LI suggests stronger desynchronization in the hemisphere contralateral to the imagined movement: C4 for left (L) and C3 for right (R) MI [7].

Statistical analysis: Normality was evaluated using the Shapiro-Wilk test and was satisfied for all variables. Task-related differences in ERD power and LI were assessed using a one-way repeated-measures ANOVA ($\alpha = 0.05$) within each session with Bonferroni correction.

Linear mixed-effects modeling: Linear mixed-effects (LME) models were used to evaluate the influence of experimental factors on ERD power, with subject included as a random effect to account for inter-individual variability. Candidate models incorporated fixed effects for feedback, stimulation condition and intensity, electrode (C3/C4), MI side and VMIQ score, including relevant interactions. Models were compared using the Bayesian Information Criterion (BIC) and the best-fitting model included main effects of feedback modality and stimulation condition, as well as an interaction between electrode location and MI side.

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RESULTS

In terms of ERD, most subjects are able to induce strong desynchronization across sessions and tasks (Figure 2), with generally stronger at contralateral electrodes (C3/C4 at the population level). For left MI, in No VR condition, sham weakened ERD and tACS restored it. A significant main effect of task was observed at contralateral C4 ($p = 0.042$), although Bonferroni-corrected post-hoc comparisons were not significant (Task 1 vs. Task 2: $p = 0.091$; Task 1 vs. Task 3: $p = 1.000$; Task 2 vs. Task 3: $p = 0.221$). In VR, sham strengthened contralateral ERD, whereas tACS hindered it at both electrodes and no significant task effects were detected. For right MI, effects were modest. In No VR, sham and tACS slightly enhanced ipsilateral ERD, with no significant task effects. In VR, sham weakened ipsilateral ERD and tACS slightly improved it, while contralateral ERD remained relatively stable across tasks, with no significant differences.

In terms of lateralization, LI values were generally positive, particularly in VR, indicating contralateral dominance (Figure 3). In No VR, median LI increased from Task 2 to Task 3, suggesting a possible tACS-related effect, with a trend toward a main effect of task ($p = 0.052$), although not significant. In VR, median LI values remained similar across tasks and no main effect of task was observed ($p = 0.734$). Overall, LI distributions were comparable between sessions and tasks.

In terms of the linear modeling, Table 2 reports significant fixed effects from the best-fitting LME model. Compared to C3, ERD at C4 was significantly more negative, indicating stronger desynchronization. Sham stimulation was associated with less negative ERD, reflecting reduced desynchronization. A significant electrode × MI side interaction showed that ERD at C4 during right MI was attenuated relative to main effects.

Finally, in terms of the neuromodulatory effects, Table 3 indicates that few sessions reached EF magnitudes (0.1 V/m) commonly associated with neuromodulation [16]. Such values were observed in both sessions for S03, S04 and S11, and only in the VR session for S05, S07 and S08. The highest EF was 0.154 V/m (S07, VR), while the lowest was 0.051 V/m, observed in multiple sessions.

Table 2: Statistically significant fixed effects from the best-fitting LME model predicting ERD.

	Estimate	$p-value$
(Intercept)	-17.203	0.009
C4	-7.251	0.020
Sham	6.737	0.013
C4*Right_MI	19.052	< 0.001

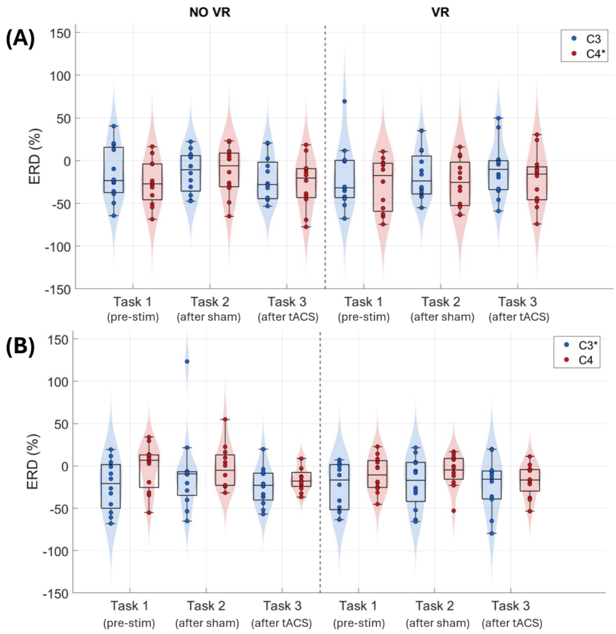

Figure 2: Boxplots showing ERD values at electrodes C3 and C4 during left (A) and right MI (B). Each boxplot presents both sessions (No VR and VR), each with three boxes representing the different tasks. The asterisk (*) indicates the contralateral electrode relative to the imagined movement.

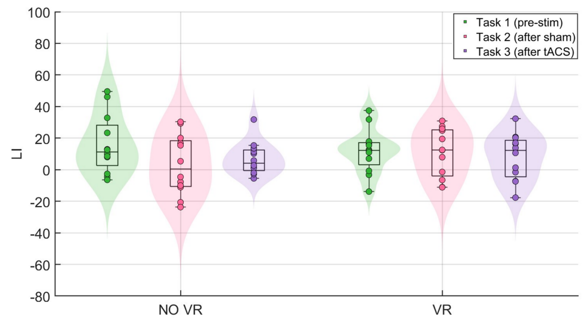

Figure 3: Boxplot of LI values comparing No VR and VR sessions, each with the three tasks.

Across analyses, substantial inter-subject variability was evident, consistent with previous literature [21–23], and reflected in the ERD distributions (Figures 2 and 3). Desynchronization was not restricted to primary motor areas but extended to parietal and occipital regions, especially in VR. This widespread pattern likely reflects increased reliance on visuospatial processing, possibly due to the relative complexity and unfamiliarity of the rowing task [24]. In line with prior findings [25], MI engages motor and premotor regions but also recruits visual areas, particularly when motor representations are less established. Stronger contralateral ERD was observed during left MI, potentially reflecting that, although imagining the rowing movement was generally challenging, imagery involving the non-dominant hand (the left hand, given that all participants were right-handed) may have been perceived as even more demanding. Instead of reducing engagement, this increased difficulty may have prompted greater effort, leading to stronger contralateral

DISCUSSION

To our knowledge, this is the first study to examine the synergistic effects of personalized-frequency tACS and a VR-BCI paradigm on the induction of ERD during MI. We aimed to determine whether adding tACS to VR-based MI enhances BCI outcomes during MI tasks.

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Table 3: IAF (Hz) and tACS (μA) and EF magnitudes (V/m) for each subject under both VR and No VR sessions. Highlighted cells indicate sessions in which the delivered EF exceeded 0.1 V/m.

	NO VR			VR		
	IAF (Hz)	**tACS magn** (μA)	**EF** (V/m)	**IAF** (Hz)	**tACS magn** (μA)	**EF** (V/m)
S01	10.260	300	0.077	9.800	300	0.077
S02	9.490	200	0.051	9.540	200	0.051
S03	10.160	500	0.128	10.160	400	0.102
S04	10.310	400	0.102	10.280	500	0.128
S05	10.180	200	0.051	10.290	400	0.102
S06	9.460	200	0.051	9.570	300	0.077
S07	9.330	300	0.077	8.960	600	0.154
S08	10.630	300	0.077	10.510	400	0.102
S09	10.360	200	0.051	9.930	200	0.051
S10	10.050	200	0.051	10.380	200	0.051
S11	9.820	500	0.128	9.690	400	0.102
S12	9.540	300	0.077	9.670	300	0.077

desynchronization regardless of spatial focality.

Consistent with the literature ([7]), ERD was generally stronger at contralateral electrodes, indicating preserved physiological lateralization (see Figures 2 and 3). Moreover, VR sessions tended to elicit stronger ERDs consistent with previous studies [8, 26] that show that MI together with motor-observation (MO) lead to greater brain activation. In the No VR sessions, tACS appeared to enhance desynchronization compared with sham, particularly during left MI, where a significant task effect at C4 was observed ($p = 0.042$), although post-hoc comparisons were not significant. In contrast, no significant ERD effects were found in VR, suggesting that VR feedback may attenuate or mask tACS-related modulation. A similar pattern was observed for LI (Figure 3): a trend toward increased contralateral dominance after tACS emerged in No VR, but not in VR. This visual trend is consistent with the statistical analysis, which revealed a trend toward a main effect of task on LI in the No VR session that, however, did not reach the predefined level of significance ($p = 0.052$). Despite limited statistical significance here, prior studies show that tES, particularly tACS, can enhance BCI classification accuracy [13] and strengthen ERDs [27]. Our results suggest that while tACS may facilitate the ERD during MI under conventional conditions, its interaction with VR feedback may attenuate or reverse these effects, warranting further investigation.

The LME analysis confirmed stronger ERD at C4, suggesting that left MI elicited stronger ERD than right MI) and revealed a significant interaction between electrode and MI side, consistent with contralateral organization. Sham stimulation was associated with weaker ERD, supporting evidence that sham is not physiologically inert and may influence cortical activity over time through expectancy or sensory factors.

Estimated EF magnitudes (presented in Table 3) varied substantially, and only a minority of sessions exceeded commonly cited neuromodulatory thresholds [16]. Higher EF was not consistently associated with stronger ERD. Notably, several VR sessions with higher EF coincided with those in which pronounced counterproductive effects of tACS on ERD were observed. Although this co-occurrence does not imply causality, it supports the possibility that higher tACS intensities may interact unfavorably with VR feedback. While no universal EF threshold exists and individual sensitivity varies, the need to preserve blinding led to reduced stimulation intensities in some participants, likely limiting neuromodulatory impact and increasing variability.

CONCLUSION

This study evaluated whether adding personalized-frequency tACS to a VR-based MI-BCI paradigm enhances ERD modulation. VR-BCI elicited stronger and more widespread contralateral ERDs compared to non-VR MI. In contrast, tACS effects were modest and primarily observable in the absence of VR, with variable or attenuated responses during immersive feedback. EF magnitude was not clearly related to ERD strength.

Overall, while tACS influenced MI-related dynamics, its added value within VR-BCI frameworks remains uncertain. Larger studies with optimized stimulation protocols are required to clarify its role in hybrid neurorehabilitation strategies.

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