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Proteus Effect in VR-Based BCI: How Avatar Age Influences Motor Imagery Behavior and EEG

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ABSTRACT: The Proteus Effect suggests that embodying avatars in virtual reality (VR) with specific characteristics can activate related stereotypes and alter behavior. While prior work has shown that avatar age influences motor imagery (MI) performance, its impact on MI-related EEG activity remains unclear. This pilot study investigated whether avatar age modulates both behavioral and EEG markers relevant for MI-based Brain–Computer Interfaces (BCIs). Sixteen healthy young adults performed a walking MI task in VR while embodied in either a young or elderly gender-matched avatar. Age-related beliefs, embodiment, mental chronometry, and Alpha event-related desynchronization/synchronization (ERD/ERS) were assessed. Participants endorsed age-related physical decline stereotypes and reported comparable embodiment across conditions. MI duration tended to be consistently longer when embodied in the elderly avatar. However, ERD/ERS analyses revealed modest and highly variable responses, with no consistent neural modulation across conditions.

INTRODUCTION

Brain–Computer Interfaces (BCIs) have received increasing attention in recent years in the field of post-stroke neurorehabilitation [1]. When combined with Motor Imagery (MI), without actual motor execution [2], BCIs can help stimulate damaged motor-related brain areas and promote neuroplasticity through repeated and vivid imagination of movements [3], helping post-stroke patients to recover lost motor function [4]. Providing visual feedback of the imagined movement further enhances this process, as action observation also activates motor-related brain regions. In this way, Virtual Reality (VR) has become an important tool to deliver such feedback in MI-BCI systems, since it creates accessible, immersive, and ecologically valid environments [5]. A key advantage of VR is its ability to induce a Sense of Embodiment (SoE), the experience of perceiving a virtual avatar as one's own body [6], which research suggests strengthens the potential for increased rehabilitation outcomes [7].

Beyond embodiment itself, avatar characteristics also shape users' cognition and behavior. In 2007, Yee, Bailenson [8] demonstrated that individuals adjust their behavior to match the traits and stereotypes associated with their embodied avatars, a phenomenon termed as the Proteus Effect. In their experiments, participants who embodied taller or more attractive avatars subsequently behaved more confidently in social interactions. Since then, numerous studies have replicated and extended these findings, showing that avatar characteristics can influence social attitudes [9], cognitive performance [10], motor behavior and physical performance [11], emotional states [12], and creativity [13]. Despite increasing evidence, the mechanisms underlying the Proteus Effect remain insufficiently understood. Most studies have focused on behavioral and self-reported outcomes, while few have examined physiological correlates. Some evidence suggests that the occurrence of the Proteus Effect may influence physiological responses such as skin conductance[14], muscle activity[15], or heart rate[16]. However, direct investigation of neural activity associated with the Proteus Effect remains lacking.

Importantly, emerging evidence indicates that the Proteus Effect may also influence MI performance. For example, Beaudoin et al. [17] embodied participants in either a female young or elderly avatar while performing a walking MI task. The results showed that participants completed the task slower when embodying the elderly avatar, with this effect being stronger in those holding more negative beliefs about older adults' motor abilities. These findings suggest that avatar characteristics can modulate mentally represented physical activity, highlighting the potential relevance of the Proteus Effect in MI-based paradigms.

Given that MI-BCI performance relies on specific neural signatures, such as Alpha event-related desynchronization/synchronization (ERD/ERS) [2], any factor that can modulate MI-related brain activity may directly influence MI-BCI performance. Therefore, the present study aims to induce the Proteus Effect within an MI context and evaluate its impact on EEG activity relevant to MI-BCI training, specifically examining whether avatar age can modulate lower-limb MI-related brain patterns. Given the previous findings on the impact of Proteus Effect on MI performance [17] and evidence suggesting its influence on physiological signals [14–16], this study aims to replicate the findings of previous research and extend it further by investigating whether such effects are reflected in neural activity patterns.

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MATERIALS AND METHODS

Participants: A total of 16 participants were included in this study (8 males (50%); 8 females (50%); age: 21.94 ± 2.77 years). 15 participants were right-handed and one was left-handed, without any known neurological conditions. All participants provided written informed consent 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.

Experimental design: The experimental design was based on the procedure described in Beaudoin et al. [17], with extensions to include EEG acquisition and additional MI tasks (Figure 2). Upon arrival, participants provided their informed consent and completed a set of questionnaires, specifically, demographic information, and the General Beliefs about Physical Functioning Instrument (GBPFI) [18]. The GBPFI assessed beliefs regarding the extent to which a typical person aged 20–90 years (in decades) possesses four physical abilities (strength, balance, gait speed, and flexibility). Responses were provided on a continuous vertical visual analogue scale ranging from 0 (lowest possible ability) to 1200 (highest possible ability), with participants being blind to the numerical values.

The VR headset was placed over the electrodes and remained on throughout the session. A 4-minute resting-state EEG recording was acquired in VR consisting of a black background with a central white fixation cross: 2 minutes eyes-open (fixating the cross), followed by 2 minutes eyes-closed.

Participants subsequently completed two experimental conditions in a randomized order (within-subject design): Elderly condition (participants embodied an elderly avatar) and Young condition (participants embodied a young avatar), with a break in between. In both, participants embodied a gender-matched avatar from a first-person perspective, while the alternative-age avatar (i.e., the non-embodied avatar) was seated beside the self-avatar and remained visible throughout the task. This ensured continuous visual exposure to both age representations and the activation of age-related stereotypes (Figure 1). Each condition comprised four runs (with a brief pause midway), and each run included three tasks:

1. Embodiment task: Participants remained seated and performed repetitive elbow flexion (approximately one movement per second, $\approx 45°$ angular amplitude), while observing the self-avatar mirror their movements in real time. The task consisted of 10s baseline, 30s right-arm movement, 10s baseline, and 30s left-arm movement, with auditory cues marking movement onset and offset.

2. MI upper limbs task: Participants performed an MI task consisting of repeatedly imagining the same elbow flexion movement performed during the Embodiment task. Each trial began with a 10 s baseline (fixation cross between the avatar's arms), followed by a directional cue indicating the left or right arm, and 10 s of the MI task. No avatar movement was present. Each run included 10 trials (5 per arm), presented in randomized order.

3. MI lower limbs task: Participants were instructed to perform a walking MI task. They first turned their head to the right toward a virtual corridor, where a chair appeared at one of five randomized distances. After the chair appeared, they imagined standing up, walking to the chair, and sitting down (MI task). Trials were initiated by pressing a button and closing their eyes; upon completing the imagined movement, participants pressed the button again and reopened their eyes. Button presses were used to record mental chronometry. Each run included five randomized trials (one per distance).

Thus, across the four runs per condition, participants completed 4 embodiment trials per arm, 20 MI upper limb trials per arm, and 20 MI lower limb trials (4 per chair distance).

At the end of each condition, participants completed the Embodiment Questionnaire (EQ) [19], consisting of 16 items rated on a 7-point Likert scale and estimated the self-avatar's age. At the end of the session, they were also immersed in gender-mismatched versions of both the elderly and young avatars and estimated their age to control for potential confounding effects of avatar characteristics (e.g., gender) on perceived age.

Experimental setup: The EEG setup used 32 active electrodes arranged according to the 10–20 system, with the reference electrode placed at FCz and ground electrode on the forehead. EEG signals were acquired at a sampling rate of 250 Hz using a LiveAmp 32 EEG amplifier (Brain Products GmbH, Gilching, Germany). Resting-state EEG signals were recorded using BrainVision Recorder (Brain Products GmbH, Gilching, Germany). To synchronize signals with experimental events the Lab Streaming Layer (LSL) was used.

The VR environment was adapted from Beaudoin et al. [17] (Figure 1), and developed in Unity game engine (Unity Technologies, USA). It consisted of a three-dimensional room with parquet flooring and wallpaper-covered walls, with two avatars seated side by side at a virtual table facing a mirror (a young adult and an elderly adult avatar). Depending on the experimental condition, participants embodied either the young or the elderly avatar (self-avatar), while the other remained as a static other-avatar to their left, visible directly and in the mirror. A corridor became visible when participants rotated their head approximately 90° to the right, where a virtual chair could appear at five equally spaced distances: Chair 1 (closest) through Chair 5 (farthest).

Participants experienced and controlled the avatars using an Oculus Rift CV1 headset (Oculus VR, Meta, Inc., USA), together with Oculus Touch controllers. Head rotation was mapped to the self-avatar's head orientation, while upper-limb movements were tracked via the controllers, with sagittal inclination corresponding to elbow flexion.

EEG signal analysis: EEG signals recorded during

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Figure 1: Overview of the experimental setup (upper-left corner) and the virtual environment. The top-right image shows the virtual corridor located on the right side. The bottom images present the young and elderly avatars for the male (left) and female (right) versions of the scenario.

the closed-eyes resting state and the MI lower limbs task were processed post-hoc using the EEGLAB toolbox (v2023.1) in MATLAB R2022a.

The signals were first downsampled to 125 Hz and bandpass filtered (1 to 40 Hz). Channels were evaluated using EEGLAB's automatic rejection criteria, including flatline detection (>5s), low correlation with neighboring electrodes (Pearson correlation < 0.8; neighbors defined in Euclidean sensor space), line-noise levels (>4), and power spectral density inspection. Bad channels were manually removed and subsequently interpolated. Next, Independent Component Analysis (ICA) was performed, and artifactual components were rejected using ICLabel combined with visual inspection. Artifact Subspace Reconstruction (ASR) was applied to correct high-amplitude artifacts without removing data segments. Finally, signals were re-referenced to the common average.

For the MI lower limbs task, data segments corresponding to the period from task onset to task completion (as determined by individual mental chronometry timings, e.g., approx. 4-12s) were extracted for each MI trial. Since this task was not time-locked, epoch duration varied across trials and fixed-length epoching was not applicable.

Event-Related Spectral Perturbations (ERSPs) were computed for the total duration of each MI lower limbs trial individually, using the closed-eyes resting-state recording (5–120 s) as baseline. ERSPs capture changes in spectral power relative to baseline across the time–frequency domain, from which ERD/ERS was derived as the percentage change in power relative to baseline[2]. ERD/ERS values were averaged over the Alpha frequency band (8–12 Hz) and across time (entire trial duration), obtaining a single-trial measure. This approach was preferred over full time-frequency pattern analysis, as the variable epoch lengths preclude meaningful temporal alignment across trials. Mean ERD/ERS values were then computed (i) across all chair distances combined and (ii) separately for each chair distance, resulting in six values per subject:

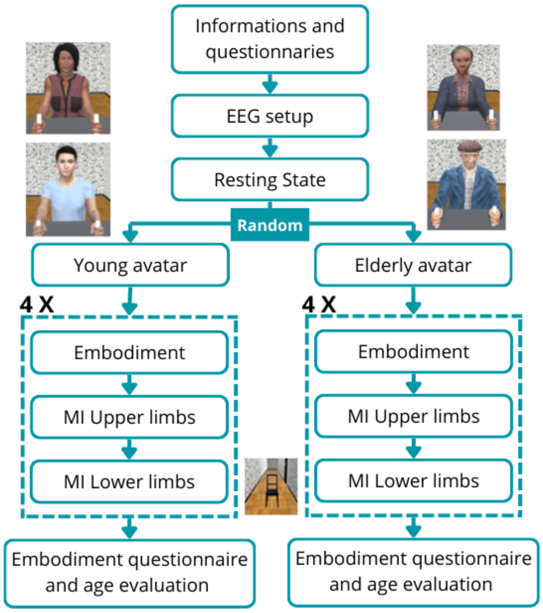

Figure 2: Schematic representation of the data collection procedure.

one representing the mean across all chairs and five corresponding to Chairs 1 through 5 individually, for both conditions (Young vs. Elderly).

Statistical analysis: Mental chronometry and ERD/ERS during lower-limb MI trials were compared between Young and Elderly conditions. ERD/ERS values were restricted to electrodes C3, C4, and Cz, and analyzed considering (i) all chair distances combined and (ii) each chair distance individually. These electrodes were selected because they overlie sensorimotor cortical areas, which are expected to be engaged during MI tasks[2]. Due to the reduced sample size, the non-parametric Wilcoxon signed-rank test was applied for all condition comparisons, with a significance level of 0.05. P-values were corrected using FDR multiple-comparison correction, applied separately for mental chronometry times and ERD/ERS values.

RESULTS

Perceived Aging and Embodiment: Participant beliefs about age-related changes, as reported by the GBPFI, show that physical strength, walking speed, balance, and flexibility decrease with age, indicating that the age-related stereotype necessary to elicit the Proteus Effect was indeed present (Figure 3). Regarding the SoE, as assessed by the Embodiment Questionnaire, participants reported comparable levels between conditions (Young condition: 4.31 ± 1.17 and Elderly condition: 4.42 ± 1.08, in a 7-point Likert scale; $p = 0.50$). Additionally, participants perceived the elderly avatars as significantly older than the young avatars (male avatars: elderly 74.06 ± 7.81 years vs. young 19.00 ± 2.68 years, $p < 0.001$; female avatars: elderly 81.31 ± 6.31 years vs. young 34.06 ± 4.54 years, $p < 0.001$).

Mental chronometry: Mental chronometry results indi-

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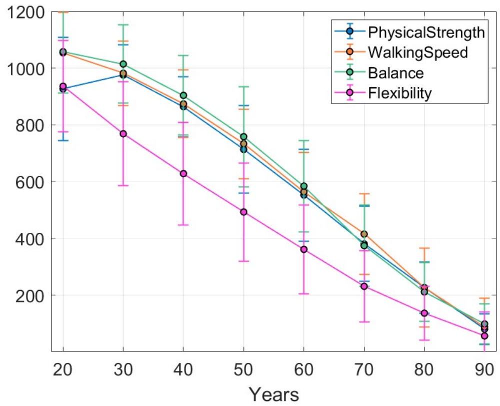

Figure 3: Mean (±SD) ratings of the GBPFI questionnaire, on the 0–1200 scale, for perceived physical strength (blue), walking speed (orange), balance (green), and flexibility (pink) across age decades (20–90 years).

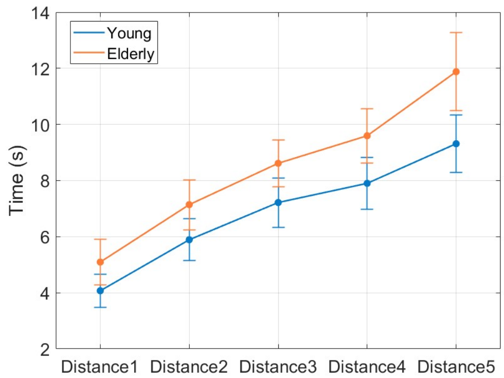

Figure 4: Mean (±SD) mental chronometry time (in seconds) for the MI lower limb task across chair distances (1 to 5) in the Young (blue) and Elderly (orange) conditions.

cate that the time required to perform the MI lower limb task increased with the virtual distance of the chair, and participants consistently tended to take longer to perform the MI task when embodied in the elderly avatar compared to the young avatar (Figure 4). Although no significant differences between conditions were observed, a trend towards a main increase in MI duration in the Elderly condition was observed for chair distance 1 (Young: 4.07 ± 2.36 s; Elderly: 5.10 ± 3.24 s; $p = 0.08$), chair distance 2 (Young: 5.89 ± 2.98 s; Elderly: 7.14 ± 3.56 s; $p = 0.06$), chair distance 3 (Young: 7.22 ± 3.51 s; Elderly: 8.62 ± 3.32 s; $p = 0.06$), and chair distance 4 (Young: 7.90 ± 3.71 s; Elderly: 9.60 ± 3.87 s; $p = 0.06$). Only for chair distance 5 (Young: 9.31 ± 4.06 s; Elderly: 11.88 ± 5.56 s; $p = 0.15$) this trend was not as strongly observed, despite the Elderly condition still showing considerably longer MI times compared to the Young condition.

ERD/ERS Patterns During Lower-Limb MI: During lower-limb MI, ERD was induced over central sensorimotor regions as expected (Figure 5). However, this pattern was not consistently reflected at the electrodes of interest (C3, Cz, C4), and no consistent ERD/ERS pattern emerged when considering all chair distances. No significant difference between conditions was observed at any electrode (Table 1), and both conditions showed ERS rather than the expected MI-induced ERD, with this effect being more pronounced in the Elderly condition.

A chair-by-chair analysis yielded similar results. The C4 electrode showed ERD for chair distance 1, 3, 4, and 5 in the Young condition, and for chair distance 1 in the Elderly condition. However, these effects were small and neither condition demonstrated robust or consistent ERD. Still, significantly lower values were observed in the Young condition compared to the Elderly condition for chair distance 4 across all electrodes of interest. No significant differences were found for the remaining chairs (Table 1), although values were generally lower in the Young condition.

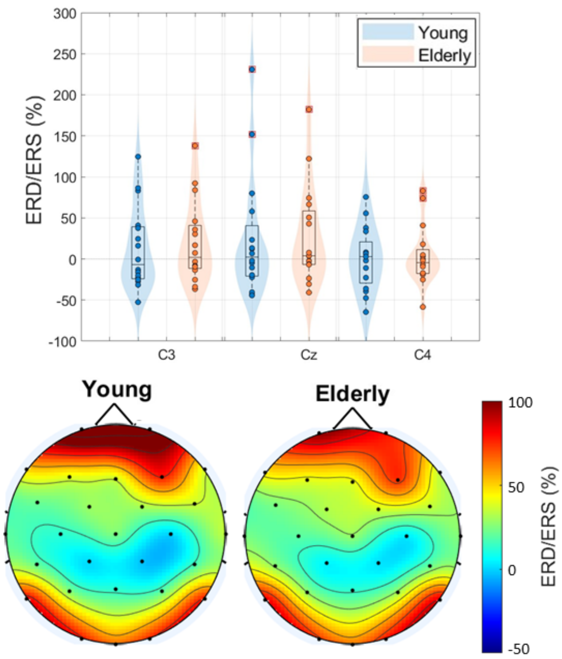

Figure 5: Grand-average ERD/ERS for the Young (blue) and Elderly (orange) conditions during the MI lower limbs task. The top panel shows boxplots of ERD/ERS at C3, Cz and C4, and the bottom panel presents the topographical map of mean changes, where negative values (blue) indicate ERD and positive values (red) indicate ERS.

DISCUSSION

This study aimed to extend the behavioral impact of the Proteus Effect on MI performance reported by Beaudoin et al. [17] and to examine whether it also modulates neural activity during lower-limb MI, specifically in Alpha ERD.

Participants exhibited the expected age-related stereotypes (Figure 3), reporting that physical abilities decline with age. This was essential, as the Proteus Effect relies on the activation of internalized stereotypes asso-

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Table 1: Mean ERD/ERS (%) across all chair distances in the MI lower limbs task, and p-values from the Wilcoxon signed-rank test comparing Young vs. Elderly self-avatar conditions at C3, Cz and C4. * denotes statistically significant differences.

	All Chairs			**Chairs 1**			**Chairs 2**			**Chairs 3**		
	Young	**Elderly**	**p-value**	**Young**	**Elderly**	**p-value**	**Young**	**Elderly**	**p-value**	**Young**	**Elderly**	**p-value**
C3	12.72	19.40	0.06	4.60	13.07	0.71	20.81	9.33	0.69	14.66	21.10	0.41
Cz	24.36	27.52	0.47	27.50	23.09	0.71	32.06	24.14	0.80	22.42	25.27	0.41
C4	0.36	3.81	0.47	-2.76	-7.11	0.72	7.76	5.02	0.80	-0.96	4.46	0.41

	Chairs 4			**Chairs 5**		
	Young	**Elderly**	**p-value**	**Young**	**Elderly**	**p-value**
C3	8.09	29.50	0.03*	15.43	23.99	0.12
Cz	18.71	33.54	0.03*	21.13	31.55	0.12
C4	-0.69	10.17	0.03*	-1.54	6.48	0.12

ciated with avatar characteristics [8]. Embodiment ratings were moderate (approximately 4 on a 7-point scale) and comparable across conditions, indicating that participants experienced a similar SoE in both elderly and young avatars. Moreover, these levels were consistent with those reported by Beaudoin et al. [17]. Although embodiment is inherently subjective, these results suggest that participants were sufficiently embodied in the avatars, another critical factor for eliciting the Proteus Effect[8]. Together, these findings indicate that the necessary psychological conditions (age-related stereotypes, accurate age perception, and comparable embodiment) were present.

Behaviorally, the effect was reflected in the mental chronometry task (Figure 4), supporting the successful induction of the Proteus Effect. Imagined walking time increased with chair distance, demonstrating temporal congruency between imagined duration and implied physical effort. Importantly, participants consistently tended to take longer to complete the MI task in Elderly condition compared to the Young condition across all distances, even though no statistical significance was observed. This lack of significance may be attributed to the small sample size, inter-individual variability, and the relatively short task duration (4-12 seconds) which may not be enough to see differences. Moreover, these results closely replicate the pattern reported by Beaudoin et al. [17], supporting a behavioral manifestation of the Proteus Effect and suggesting that avatar age influenced the temporal representation of imagined movement.

In contrast to the behavioral findings, the EEG results were less conclusive. When considering all chair distances together, ERD values were generally modest and highly variable across participants. In several cases, Alpha-ERS rather than ERD was observed, and no consistent pattern emerged for any condition. Even in the chair-by-chair analysis, where subtle fluctuations were present, no robust or systematic ERD modulation was detected. Several factors may explain the absence of clear ERD modulation. First, ERD/ERS was computed using a closed-eyes baseline acquired at the beginning of the session and potential baseline drifts may have reduced sensitivity. Second, the MI task was performed without visual feedback, which typically strengthens ERD responses [20], possibly attenuating sensorimotor engagement. Additionally, lower-limb MI generally elicits weaker and more centrally localized ERD due to its deeper cortical representation [21], making detection with scalp EEG more challenging, particularly in untrained participants, as in the present study. Finally, substantial inter-individual variability (Figure 5) may have masked subtle condition-related effects.

Nevertheless, Alpha power in the Young condition generally showed lower ERS compared to the Elderly condition for chair distance 1, 2, 4 and 5, as well as for all chairs together (Table 1) , even reaching statistical significance for chair distance 4. This finding may suggest a potential interaction between avatar age representation and ERD/ERS patterns. Moreover, the fact that only chair distance 3 (Table 1) present a different trend between conditions may also indicate a possible influence of distance. However, given the absence of consistent ERD patterns, interpretation remains speculative.

Overall, under the present experimental conditions, the Proteus Effect did not produce a clear modulation of ERD during walking MI. While behavioral effects were robust, neural differences were subtle and inconsistent, suggesting that avatar-induced modulation may primarily influence cognitive aspects of MI rather than strongly altering brain patterns. Importantly, these findings should be interpreted cautiously, as they are preliminary and subject to several limitations. The sample size was relatively small, participants were mostly inexperienced in MI tasks, and the sample included only young adults. Additionally, the absence of visual feedback during MI, the button press used to initiate mental chronometry, and methodological factors such as baseline selection for ERD computation may have influenced neural activity and reduced sensitivity to task-related effects.

Future work will focus on increasing the sample size to improve statistical power and sensitivity to subtle neural effects, as well as expanding EEG analyses during lower-limb MI in both time and frequency domains. Exploration of potential correlations between ERD, mental chronometry, and questionnaire measures (e.g., GBPFI) will also be conducted, as well as explore possible effects of imagined walking distances. Lastly, examining EEG activity during embodiment and MI upper limbs tasks may provide further insight into possible neural modulation associated with the Proteus Effect.

CONCLUSION

This study extended and confirmed prior findings on the

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behavioral impact of the Proteus Effect on MI and examined whether it also modulates neural activity during a walking MI task. Clarifying how avatar-induced effects influence MI-related neural signatures, such as ERD, is relevant for optimizing visual feedback in MI-BCI systems. Behavioral results were consistent with the Proteus Effect, as participants required longer imagined walking times when embodied in an elderly avatar compared to a young avatar. However, this modulation did not translate into robust or consistent ERD/ERS differences. Although subtle trends toward lower Alpha synchronization in the Young condition were observed, neural effects remained modest and highly variable. These findings suggest that avatar appearance can influence behavioral representations of movement without necessarily inducing measurable changes in MI-related EEG patterns. Future studies with larger samples, the inclusion of upper-limb MI, and extended EEG analyses are needed to determine under which conditions embodiment-related factors modulate neural signatures relevant for MI-BCI applications.

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