Computers in Human Behavior 165 (2025) 108537

Contents lists available at ScienceDirect

Computers in Human Behavior

journal homepage: www.elsevier.com/locate/comphumbeh

Neuromodulation via tRNS accelerates learning and enhances in-game performance at a virtual-reality first person shooter game

Francesco Neri [a,b], Jacopo Della Toffola [a], Adriano Scoccia [a], Alberto Benelli [a], Francesco Lomi [a], Alessandra Cinti [a], Carmelo Luca Smeralda [a], Sara Romanella [c,d], Alessandro Giannotta [a], Simone Rossi [a,b], Emiliano Santarnecchi [c,d,*]

[a] *Siena Brain Investigation & Neuromodulation Lab, Department of Medicine, Surgery and Neuroscience, Neurology and Clinical Neurophysiology Section, University of Siena, Italy*
[b] *Oto-Neuro-Tech Conjoined Lab, Policlinico Le Scotte, University of Siena, Italy*
[c] *Precision Neuroscience and Neuromodulation Program, Gordon Center for Medical Imaging, Department of Radiology, Massachusetts General Hospital, Harvard Medical School, Boston, MA, USA*
[d] *Department of Neurology, Massachusetts General Hospital, Harvard Medical School, Boston, MA, USA*

ARTICLE INFO

Handling editor: Bjorn de Koning

ABSTRACT

Background: Recent studies have investigated methods for improving the acquisition of complex visuomotor skills in virtual reality (VR) settings, but the results have been inconclusive.
Objective/Hypothesis: This study aims to examine whether transcranial random noise stimulation (tRNS), a non-invasive brain stimulation technique, can accelerate the learning process of a VR first-person shooter (VR-FPS) training and its impact on gaming abilities and on cognitive functions.
Methods: After exclusion of 9 subjects due to VR-cybersickness, twenty-two healthy young volunteers (6 females, 16 males; mean age 26.5 ± 4.9 years) participated in a five-day VR-FPS training. The participants were randomly assigned to either the Active (real)-tRNS (n=11) or the Sham (placebo)-tRNS group (n=11). Each day, tRNS targeting an ad-hoc visuo-motor functional brain network was administered for the first two rounds (tRNS ON), but not in the last two rounds out of four (tRNS OFF). The difficulty of the round was adjusted according to the ratio of overwhelmed enemies (O) to the player's defeats (D): (O/D). The participants' shooting skills and cognitive abilities were evaluated before, immediately after and one week after the training (T0, T1, T2).
Results: The Active-tRNS group showed significantly higher O/D performance compared to the Sham-tRNS group ($p < .05$), particularly during tRNS OFF rounds ($p < .05$). Additionally, at T2, the Active-tRNS group exhibited significantly better performance in a long-range shooting task than the Sham-tRNS group. Both groups showed improved cognitive abilities at T1 and at T2.
Conclusions: tRNS of an hybrid visuo-motor network can enhance the learning curve of VR-FPS training, with persistent and strong after-effects. This finding has potential applications for both performance training and treatment of clinical conditions.

1. Introduction

Professional video gaming has given rise to electronic sports (e-sports) tournaments, where cyber-athletes compete for highly remunerative prizes and visibility in a large gaming community (Hutchins, 2008; Palma-Ruiz, Torres-Toukoumidis, González-Moreno, & Valles-Baca, 2022). Players train for months to prepare for a contest, making it crucial to find methods that optimize game learning. First-person-shooter (FPS) games are widely used action videogames in e-sports tournaments and recent findings have shown that personalized training, which modifies the difficulty level based on the performance, leads to a significant acceleration of the learning curve and a reduction in the time required to master the game (Neri et al., 2021).

The FPS perspective demands high degree of flexibility, task-

---

* Corresponding author: Precision Neuroscience & Neuromodulation Program, Gordon Center for Medical Imaging, Department of Radiology, Massachusetts General Hospital, Harvard Medical School, Boston, MA, USA.
E-mail address: esantarnecchi@mgh.harvard.edu (E. Santarnecchi).

https://doi.org/10.1016/j.chb.2024.108537
Received 13 May 2024; Received in revised form 6 December 2024; Accepted 8 December 2024

switching skills, and rapid reaction times (Colzato, van Leeuwen, van den Wildenberg, & Hommel, 2010). Performance in such games relies on the functioning of several cognitive and perceptual abilities, including selective attention, stimulus detection, shifting and decision-making (Castel, Pratt, & Drummond, 2005; Green & Bavelier, 2003a; Kowal, Toth, Exton, & Campbell, 2018). Additionally, frequent videogaming can enhance specific cognitive abilities such as selective attention, visuospatial attention, visuospatial memory, decision-making, multitasking, and cognitive control (Anguera et al., 2013; Bavelier, Green, Pouget, & Schrater, 2012; Green and Bavelier, 2003a, 2006a; Green, Li, & Bavelier, 2010; Greenfield, 2009). Long-term changes in specific cognitive abilities are related to video game genre: for example, FPS games appear to impact on increased perceptual ability and hand-eye coordination (Basak, Boot, Voss, & Kramer, 2008; Bediou et al., 2018; Jakubowska et al., 2021), as participants who underwent to an FPS training showed improved visuomotor control, including faster reaction times and better eye-hand coordination (Li, Chen, & Chen, 2016).

Virtual reality (VR) is an immersive technology that uses simulated 3D scenarios, in which participants report an increase in self-efficacy and sense of immersion (Radhakrishnan, Chinello, & Koumaditis, 2023). Recent advancements in accessibility and technology have made VR increasingly popular among both consumers and researchers. Beyond its entertainment value, VR has been shown to have significant benefits in diverse fields such as education, healthcare, and skill development for the workplace. (Herz & Rauschnabel, 2019; Jerdan, Grindle, Woerden, & Boulos, 2018; Zhao, Xu, Jiang, & Ding, 2020). For instance, VR has been used to investigate the effects of virtual scenarios on the learning curve of a task. A training program that focuses on fine motor skills using a VR environment can significantly enhance the functional mobility and balance performance in healthy older adults when compared to traditional training in physical environments (Liu et al., 2022). Few studies have investigated cognitive and brain activation peculiarities during VR, but data suggest a higher cognitive load during gaming in a VR environment (Roettl & Terlutter, 2018). Additionally, improved perception and emotional arousal associated with the 3D gaming lead to an higher beta band oscillation in both hemispheres (Tian, Hua, Zhang, Li, & Yang, 2021).

A VR-FPS is a game that allows players to experience the action through the eyes of their avatar, offering a heightened level of immersion compared to traditional PC-based FPS games. Typically, the player uses two controllers that simulate hand movements, enabling them to grab weapons, interact with objects, and communicate with teammates (Makarov et al., 2016). In a VR-FPS game, the full understanding of the interface and commands might require several hours of practice to reach a good level of skill. A method that optimizes the learning process and allows players to reach a top level of play more rapidly could enhance the VR experience.

Transcranial random noise stimulation (tRNS) is a non-invasive brain stimulation (NiBS) technique that involves the application of a low-intensity alternating current with a random frequency variation that can modulate the cortical activity of a brain area or a network, thereby improving the related cognitive functions (Brancucci, Rivolta, Nitsche, & Manippa, 2023; Terney, Chaieb, Moliadze, Antal, & Paulus, 2008). Usually, the entire frequency spectrum of tRNS is between 0.1 and 640 Hz and this spectrum is by convention split into two: the low-frequency tRNS (lf-tRNS) with a spectrum of 0.1–100 Hz and the high-frequency tRNS (hf-tRNS) with a spectrum of 100–640 Hz (Antal & Herrmann, 2016; Fertonani, Pirulli, & Miniussi, 2011; Moret, Donato, Nucci, Cona, & Campana, 2019; Potok, van der Groen, Bächinger, Edwards, & Wenderoth, 2021). tRNS is capable of inducing LTP-like plasticity after-effects (Terney et al., 2008) and it might act at the neural membrane level by favouring the opening of Na + channels (Chaieb, Antal, & Paulus, 2015), or exerting its effects through the concept of "stochastic resonance" of a neural signal (Remedios et al., 2019). Recent studies have focused on hf-tRNS, which has yielded better results in terms of neurocognitive enhancement, e.g. in the visual recognition and discrimination function (Contemori, Trotter, Cottereau, & Maniglia, 2019), in the discernment of emotional facial expressions (Penton, Dixon, Evans, & Banissy, 2017), in attention (Tyler, Contò, & Battelli, 2018), in perception (Liu, Wu, Wang, Zhang, & Zhang, 2023), in processes of learning (Battelli et al., 2022; Pirulli, Fertonani, & Miniussi, 2013), and decision-making (Vd Groen et al., 2018). In addition, recent studies have shown that coupling tRNS with perceptual learning can successfully enhance the training effect across sessions, with subsequently observed behavioral improvements persisting in the long term (Contò et al., 2021; Fertonani et al., 2011). The application of tRNS was observed to facilitate reaction times and improve learning rates in the context of arithmetic learning, particularly in the challenging condition characterised by a reduced number of problem repetitions. This suggests that tRNS may enhance numerical cognition, with effects potentially mediated by the learning system (Popescu et al., 2016).

In the current randomized, sham-controlled study, tRNS was optimized to stimulate the brain hubs responsible for visuomotor functions, specifically those recruited during an FPS game training, i.e., an hybrid visuo-motor brain functional network (Momi et al., 2021). The gaming performance, shooting abilities, and cognitive functions were assessed in participants who received real or placebo tRNS during a five-day VR-FPS training. In consideration of the findings of previous research indicating that tRNS can improve task performance (Battelli et al., 2022; Chenot et al., 2022; Contemori et al., 2019; Contò et al., 2021), it was hypothesised that the real stimulation of the visuo-motor network might cause an acceleration of the learning process during training, resulting in enhanced in-game performance compared to the participants who received a placebo stimulation. Furthermore, shooting abilities and cognitive functions were also compared between the real and placebo groups before and after the training, in order to ascertain whether the tRNS was capable of generalizing its effect beyond the gaming itself. Measurements were also taken one week after the training's completion to evaluate its long-term effects.

2. Materials and methods

2.1. General procedure

Thirty-one healthy subjects (9 females, 22 males; mean age: 26.1 ± 4.8 years), were recruited from students at the University of Siena, Italy. All participants had no history of psychiatric or neurological disorders, evaluated through Mini-International Neuropsychiatric Interview (Sheehan et al., 1998) and fulfilled a questionnaire, specifying the duration of time devoted to playing action or other types of videogames in the last 12 months (Green & Bavelier, 2006b). All participants were naïve to VR gameplay and denied to have prior experience in a VR environment. All subjects signed a written informed consent, and the protocol received approval from the local ethics committee (Protocol Name: Brainsight 21/24). There is a significant discrepancy in the number of male and female participants in the present study. However, this distribution reflects the well-established preference for FPS games among male participants (Lange, Wühr, & Schwarz, 2021). To mitigate the risk of introducing bias due to this imbalance, the gender variable has been excluded from the analysis.

A total of nine individuals were excluded from the study (~29% of participants: 3 females, 6 males; mean age: 25.1 ± 4.7 years) due to the reporting of severe symptoms of cybersickness during VR immersion. Participants were excluded on the basis of their subjective experience rather than a pre-established threshold. Subjects who experienced significant discomfort during the initial tutorial phase were withdrawn from the study. Symptoms leading to exclusion primarily included nausea, excessive sweating, and vertigo. The proportion of participants reporting severe cybersickness in this study was consistent with findings from previous research (Garrido et al., 2022).

A total of twenty-two participants (6 females, 16 males; mean age: 26.6 ± 4.9 years) underwent a randomized, sham-controlled experiment consisting of a five-day VR-FPS training. Each participant was randomly assigned to either the Active-tRNS (11 participants: 3 females; 8 males; mean age 27.9 ± 6.5 years) or the Sham-tRNS (11 participants: 3 females; 8 males; mean age 25.2 ± 2.2 years) group. Demographic characteristics and gaming questionnaire results are reported in Table S1. EEG, heart-rate (HR) and galvanic skin conductance (GSR) were also recorded between and within days. However, this study only focused on the behavioral performance and physiological data was not analysed.

2.2. Game software & VR hardware

The training was conducted using a Meta Quest 2 all-in-one VR headset with a 256 GB storage capacity and manual controllers. The headset features a fast-switching LCD display with a resolution of 1832x1920 per eye, a horizontal FoV of 97°, a vertical FoV of 93°, and supports refresh rates of 60, 72 and 90 Hz. (Oculus, Meta Platforms Inc., Menlo Park, California-USA).

The selected FPS-VR game was Contractors (https://www.meta.com/it-it/experiences/2436897736439055), a team based semi-realistic competitive multiplayer videogame with an available 90 Hz refresh rate on Meta Quest 2. The game is commonly used in professional competitions (VR-Master-League; https://vrmasterleague.com) and its interface allows the player to experience the action from the protagonist's point-of-view while performing actions such as handling weapons, engaging enemies and navigating the map. The selected game mode was team-deathmatch, which focuses on overwhelming as many members of the opposing team as possible (O factor) while avoiding defeat (D factor). The match was conducted offline, and all players, including friends and foes, were bots controlled by the software's artificial intelligence, referred to as teammates and enemy bots.

2.3. Game days

The experiment schedule consisted of five consecutive training days, each lasting approximately 2 h, for a total of ~10 h of gameplay. Each day consisted of four 20-min rounds. During each day, participants received either active or sham tRNS during only the first two rounds. Following the first two "stimulation rounds", they rested for 10 min, then the remaining two rounds were played without stimulation. This approach allowed to discriminate the online impact of tRNS on game performance (during stimulation rounds) and to evaluate whether the effects persisted in subsequent rounds (offline). Additionally, restricting tRNS to the initial daily rounds helped minimize potential confounding factors, such as participant fatigue from prolonged stimulation in a VR environment. The difficulty level increased gradually, and the player could proceed to the next level only if the O/D ratio exceeded 2:1 at the end of the round (Neri et al., 2021).

The challenge underwent several modifications, including an increase in the number of opponents, from one to five, a decrease in the number of allies from five to zero, and a change in the playing field. The map was initially large with numerous hiding sites, but became smaller by the middle of the third day, culminating in an extremely confined final arena in the final round of the fifth day. Difficulty levels were also augmented and categorized into easy, normal, and hard (Fig. 1). The skills of the enemy bots were balanced and linked to aim focus ability, aim focus interval, aim duration, reaction time, teamworking, aggressiveness, weapon proficiency and movement speed. In the easy difficulty setting, bots were designed to be less challenging, with slower reaction times, low precision in aiming, minimal aggressiveness, limited teamwork capabilities, basic weapon proficiency, and slow movement speed. The normal difficulty level increased the challenge, with bots displaying

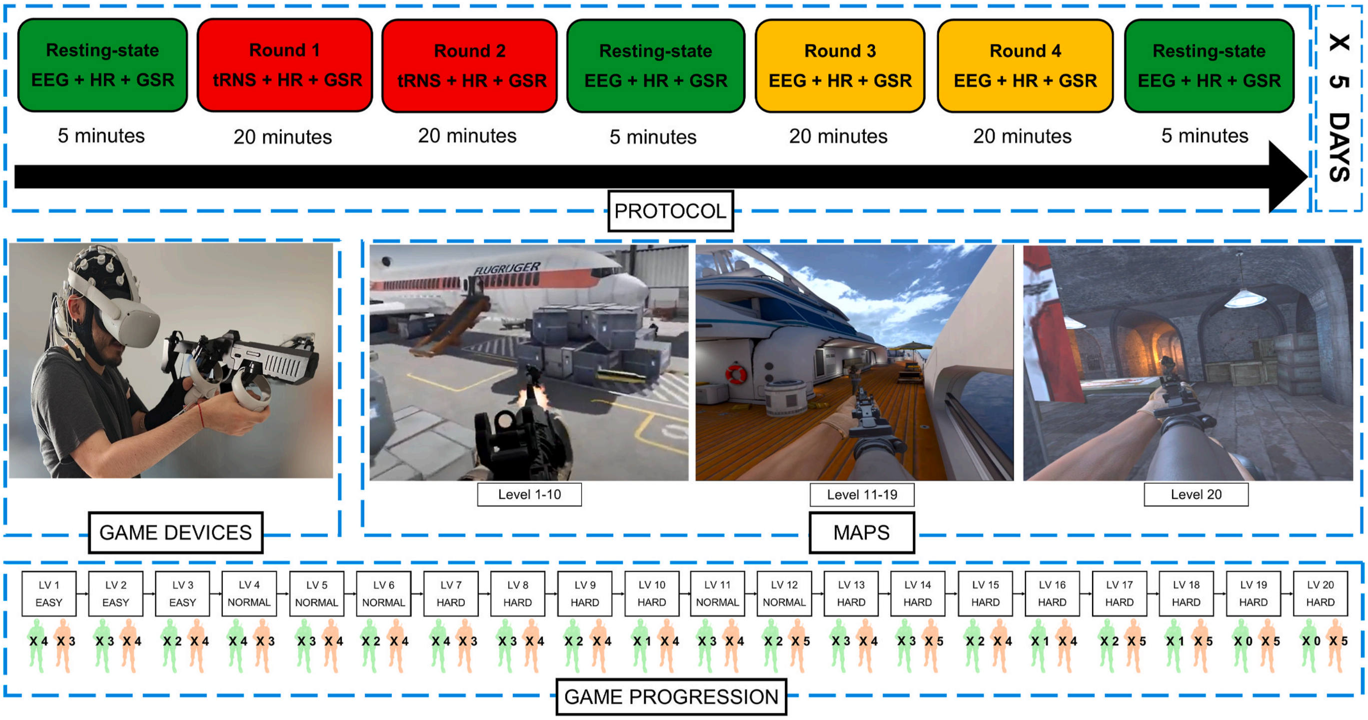


Fig. 1. Scheme of the experiment protocol. Each day, the players' resting-state electrophysiological measures were recorded, including EEG (electroencephalography), HR (heart rate) and GSR (galvanic skin response). Participants played for two 20-min rounds with either an Active-tRNS or a Sham-tRNS administration (tRNS ON: red panels). Resting-state measurements were taken again between the second and the third rounds. During the third and fourth rounds participants received no stimulation (tRNS OFF: yellow panels). A final resting-state was recorded after the last round. Players were required to play for five consecutive days, completing a total of 20 rounds. If a player achieved an O/D ratio of 2:1 or higher, they advanced to the next level, where the game difficulty progressively increased. This was accomplished by adjusting specific parameters such as the number of enemies, the difficulty level (easy, normal, hard) the number of teammates, and the map size. Three different maps were used during the training Terminal, Boat and Cellar. Terminal was the largest and easiest map, designed for the first ten levels. Boat was a smaller and more challenging map, intended for levels 11 to 19. Finally, Cellar, the smallest and most difficult map, was reserved for the final level. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

moderate reaction times, improved aiming accuracy, increased aggressiveness, better coordination with teammates, intermediate weapon proficiency, and faster movement speed. Finally, in the hard difficulty setting, bots exhibited fast reaction times, highly accurate targeting, high aggressiveness, strong teamwork strategies, advanced weapon proficiency, and rapid movement speed. These parameters were calibrated to create a progressively challenging training environment, allowing participants to improve their skills as they advanced through the game. Each participant was equipped with virtual replica weapons including an M4-Mk18 rifle, a SIG Sauer P250 gun, a fragmentation bomb, a tear gas bomb, a smoke bomb, a knife, a standard bulletproof jacket, and unlimited ammunition.

2.4. *tRNS montage and protocol*

The tRNS was administered using a Starstim 32-channel neurostimulator and delivered with NIC2.0 software (Neuroelectrics®, Barcelona, Spain) from a laptop PC via USB (Windows 11 operating system Microsoft Corporation, Redmond, Washington - USA). The stimulation montage was created using a freely available standard T1 head template (https://www.mcgill.ca/bic/software/tools-data-analysis/anatomical-mri/atlases/colin-27) and SimNIBS software (Saturnino et al., 2019). tRNS was optimized to enhance visuospatial and motor skills, targeting the Sensory Motor Network (SMN) and the Visual Network (VN), including the primary motor cortex and visual occipital regions (Thomas Yeo et al., 2011).

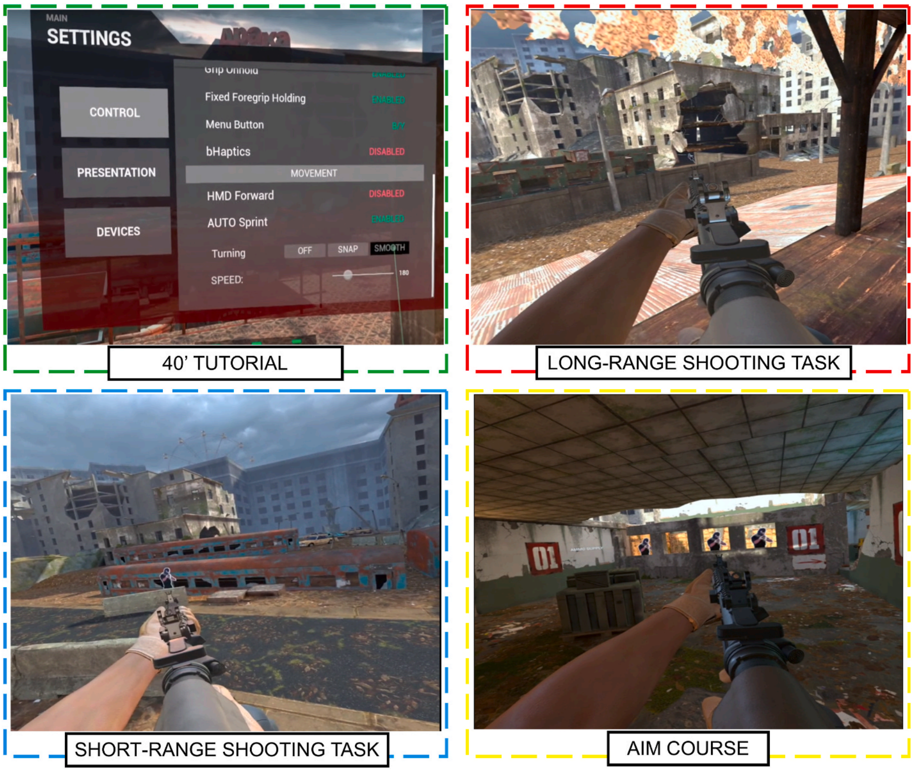
The scalp was cleaned with Microten 05 Scrub Skin (SPM S.n.c.) and an electroconductive EEG cream (Bionen s.r.l., Florence, Italy) was applied. The electrodes consisted of an upper part, containing the sintered Ag/AgCl core with a diameter of 12 mm, screwed onto a base, that covered a circular area of about 3.14 cm^2.The NG Pistim electrodes were placed on a Neoprene Headcap Pro (Neuroelectrics®, Barcelona, Spain) equipped with 64 tES/EEG electrode placeholders annotated with the 10-10 system.

The frequency range was aligned with the hf-tRNS mode (100–640 Hz). The peak-to peak current intensity was 720 μA on C1/C2, 1170 μA on C3/C4, 759 μA on P1/P2, and 1335 μA on O1/O2). In the Sham-tRNS, stimulation was applied for 30 s at the beginning and at the end of each stimulation session (ramp up and ramp down) to simulate the initial tingling sensation commonly associated with Active-tRNS. This procedure was designed to ensure that participants were unaware of whether they were receiving active or sham stimulation.

2.5. *Shooting abilities assessment*

At T0, a 40-min tutorial was conducted to ensure a complete understanding of the game interface and commands, as well as to assess for the presence of severe cyber-sickness symptoms such as nausea, dizziness and excessive sweating, which could have resulted in exclusion from the experiment.

Shooting abilities assessment (Fig. 2) occurred before, immediately after the experiment, and one week after the experiment (T0, T1 and T2). The assessment consisted of: (i) a long-range shooting task: the participant used a rifle to shoot at enemy silhouettes positioned at a distance of more than 10 m. The task accuracy was recorded; (ii) a short-range shooting task: the participant's firing accuracy was evaluated in a scenario where they were required to shoot at silhouettes of enemies within a 10-m range using a rifle; (iii) an aim course task: the player had to navigate a designated path while shooting at silhouettes of enemies that randomly appeared, using a handgun. The completion time was recorded, to measure the player's proficiency in navigating a 3D environment under time pressure conditions.



Fixed Foregrip Holding ENABLED
Menu Button B/Y
bHaptics DISABLED
MOVEMENT
HMD Forward DISABLED
AUTO Sprint ENABLED
Turning SMOOTH
SPEED: 180

Fig. 2. Tutorial phase and shooting assessment. During the initial assessment, each player completed a 40′ of tutorial to familiarize themselves with the game controls and the VR environment. At T0, T1 and T2 participants' shooting accuracy was recorded in a short-range shooting and in a long-range shooting task. In addition, the participants also completed a aim course, with the time taken to complete the task also being recorded.

2.6. Cognitive abilities assessment

Cognitive tasks were administered at T0, T1, and T2 using E-Prime 2.0 Professional (Psychology Software Tools) on a 19-inch screen placed 80 cm from the subject (Bavelier et al., 2012; Green and Bavelier, 2003a, 2004; Neri et al., 2021) to assess cognitive abilities related to videogames. The tasks used were the Visual Search, the Attentional Blink, the Serial Reaction Time Task (SRTT), and the Useful Field of View (UFOV) (see Fig. S1 in supplemental materials for details).

2.7. Cybersickness questionnaire and stimulation discomfort

After each session, the Simulator Sickness Questionnaire (SSQ) was used to assess cybersickness (Kennedy, Lane, Berbaum, & Lilienthal, 1993). The SSQ consists of 16 items, each of which is rated with on scale from none, slight, moderate to severe (see Table S2). Participants were asked to rate the symptoms severity on a scale of 0 (no perception) to 3 (severe perception) The scale enables the computation of nausea, oculomotor disturbance and disorientation subscales as well as a total score. Furthermore, participants rated their discomfort due to the stimulation protocol using a 5-point Likert scale, rating itching, pain, burning, heat, pinching, metallic taste, and fatigue symptoms (Fertonani, Ferrari, & Miniussi, 2015).

2.8. Statistical analysis

Statistical analysis was performed using SPSS version 16, SPSS Inc., Chicago, IL, USA. A preliminary one-way analysis of variance (ANOVA) was conducted to ascertain potential discrepancies between the groups at baseline in terms of in-game abilities, shooting skills and cognitive functions.

Then, a repeated measures ANOVA ($ANOVA_{RM}$) was run to test for behavioral difference during the training period and between the Active-tRNS and Sham-tRNS groups. For the analysis, the raw value of the O/D ratio was corrected by applying a weight that takes into account the difficulty of the level, i.e. the raw O/D value was multiplied by the level value. The average corrected O/D ratio for the four rounds in each session was computed. Then, the relative change (percentage) from Day 1 for each subsequent training day was calculated. The O/D performance between training days and groups was analysed (2 factors: *Corrected O/D*: 5 levels: performance at day 1, 2, 3, 4 and 5; *Group*: 2 levels: Active-tRNS and Sham-tRNS). Any significant effect was then subject to pairwise comparisons with Bonferroni correction. To evaluate both the direct effect of stimulation and its after-effects, a second analysis was conducted by separating the first two rounds with stimulation (tRNS ON) from the last two rounds without (tRNS OFF). The mean O/D performance of the tRNS ON and the tRNS OFF rounds was calculated for each day. The relative change in O/D performance between the training days on Day 1 was calculated separately for both tRNS ON and tRNS OFF conditions, employing the same factors utilized in the previous analysis (*Corrected O/D*: 5 levels: performance at day 1, 2, 3, 4 and 5; *Group*: 2 levels: Active-tRNS and Sham-tRNS).

To examine changes in performance for shooting and cognitive ability assessments, $ANOVA_{RM}$ analysis or an equivalent non-parametric Friedman test for repeated measures was carried out. *Task performance* (3 levels: performance at T0, T1, T2 for both shooting and cognitive assessment) and *Group* (2 levels: Active-tRNS and Sham-tRNS group) factors were considered. T1 and T2 performance was compared in terms of the relative change (percentage) from T0. Additionally, pairwise comparisons with a Bonferroni-correction were conducted for significant effects.

An analysis was conducted on the cybersickness symptoms. The scores of the subscales and total score were compared to those of day 1. Symptoms between groups were also compared (2 factors: *Score*: 5 levels: symptoms at day 1, 2, 3, 4 and 5; *Group*: 2 levels: Active-tRNS and Sham-tRNS).

3. Results

3.1. In-game progression

A Shapiro-Wilk test on the raw data showed that the variable was normally distributed ($p > .05$). One subject was detected as an outlier and removed from the O/D database. Thus, the analysis was conducted on twenty-one participants (Active-tRNS group: 11 participants: 3 females, 8 males; mean age 27.9 ± 6.5 years; Sham-tRNS group: 10 participants: 3 females, 7 males; mean age 25.4 ± 2.2 years). The preliminary one-way ANOVA revealed no significant differences in in-game abilities between the groups at T0 ($p > .05$).

In the analysis of the difference in O/D performance between days (Fig. 3A), a violation of the assumption of sphericity was detected by Mauchly's test (X^2 (9) $= 83.80$, $p < .001$), and a Greenhouse-Geisser correction was applied ($\varepsilon = .345$). The ANOVA revealed a significant main effect of the *Corrected O/D* factor ($F_{(1.38,\ 26.21)} = 36.54$, $p < .001$, $\eta^2 = .65$). Post hoc pairwise multiple comparison tests, corrected using the Bonferroni method, revealed significantly higher performance on days 3, 4, and 5 compared to day 1 ($p < .001$ in all comparisons). A significant interaction between the *Corrected O/D* and *Group* factors was also detected ($F_{(1.38,\ 26.21)} = 3.91$, $p = .047$, $\eta^2 = .17$). The performance of the Active-tRNS group was significantly higher than that of the Sham-tRNS group on days 3, 4, and 5 ($p = .041$; $p = .045$; $p = .047$, respectively).

The analysis of the results of tRNS ON rounds (Fig. 3B) showed that the sphericity assumption was violated (X^2 (9) $= 101.65$, $p < .001$), and a Greenhouse-Geisser correction was applied ($\varepsilon = .344$). A significant effect of the *Corrected O/D* factor was detected ($F_{(1.37,\ 26.11)} = 16.47$, $p < .001$, $\eta^2 = .73$) with a higher performance at day 4 and 5 compared to day 1 ($p = .035$ and $p = .003$ respectively). A trend towards a significant interaction between the *Corrected O/D* and *Group* factors was detected ($p. = .093$).

Regarding the analysis of tRNS OFF rounds (Fig. 3C), the sphericity assumption was violated (X^2 (9) $= 45.26$, $p < .001$), and a Greenhouse-Geisser correction was applied ($\varepsilon = .583$). A significant effect of the *Corrected O/D* factor was found ($F_{(2.33,\ 26.11)} = 31.03$, $p < .001$, $\eta^2 = .62$), with a higher performance on days 3, 4 and 5 compared to day 1 ($p < .001$; $p = .003$; $p < .001$, respectively). Lastly, a significant interaction between the *Corrected O/D* and *Group* factors was detected ($F_{(2.33,\ 44.34)} = 3.26$, $p = .041$, $\eta^2 = .14$). On days 3 and 4, the performance in the Active-tRNS group was higher than in the Sham-tRNS group ($p < .023$ and $p = .047$ respectively). Table 1 presents data from the training period in comparison to Day 1 for both the Active-tRNS and Sham-tRNS groups.

3.2. Shooting assessment analysis

A Shapiro-Wilk test was conducted on the raw data, indicating a normal distribution ($p > .05$). No significant differences were observed in shooting abilities between the Active-tRNS and Sham-tRNS groups at the baseline assessment ($p > .05$). A Mauchly's test was conducted to verify the sphericity of data for gaming assessment. Considering long-range shooting task, no assumption of sphericity was violated (X^2 (2) $= .96$, $p < .720$). For short-range shooting and aim course tasks, the assumption of sphericity was violated (X^2 (2) $= 26.99$, $p < .001$ and X^2 (2) $= 13.65$, $p = .001$) and a Huynh-Feldt correction was applied ($\varepsilon = .569$ and $\varepsilon = .661$).

The long-range shooting task analysis (Fig. 4A) showed a significant main effect of the *Task Performance* factor ($F_{(2,40)} = 22.90$, $p < .001$, $\eta^2 = .44$), with a higher performance at T1 and at T2 compared to T0 ($p = .001$ and $p < .001$). Moreover, a significant interaction between the *Task Performance* and *Group* factor was detected ($F_{(2,40)} = 3.32$, $p = .046$, $\eta^2 = .14$), with the Active-tRNS group showing a better performance at T2 compared to the Sham-tRNS group ($p = .028$).

The short-range shooting task analysis (Fig. 4B) revealed a

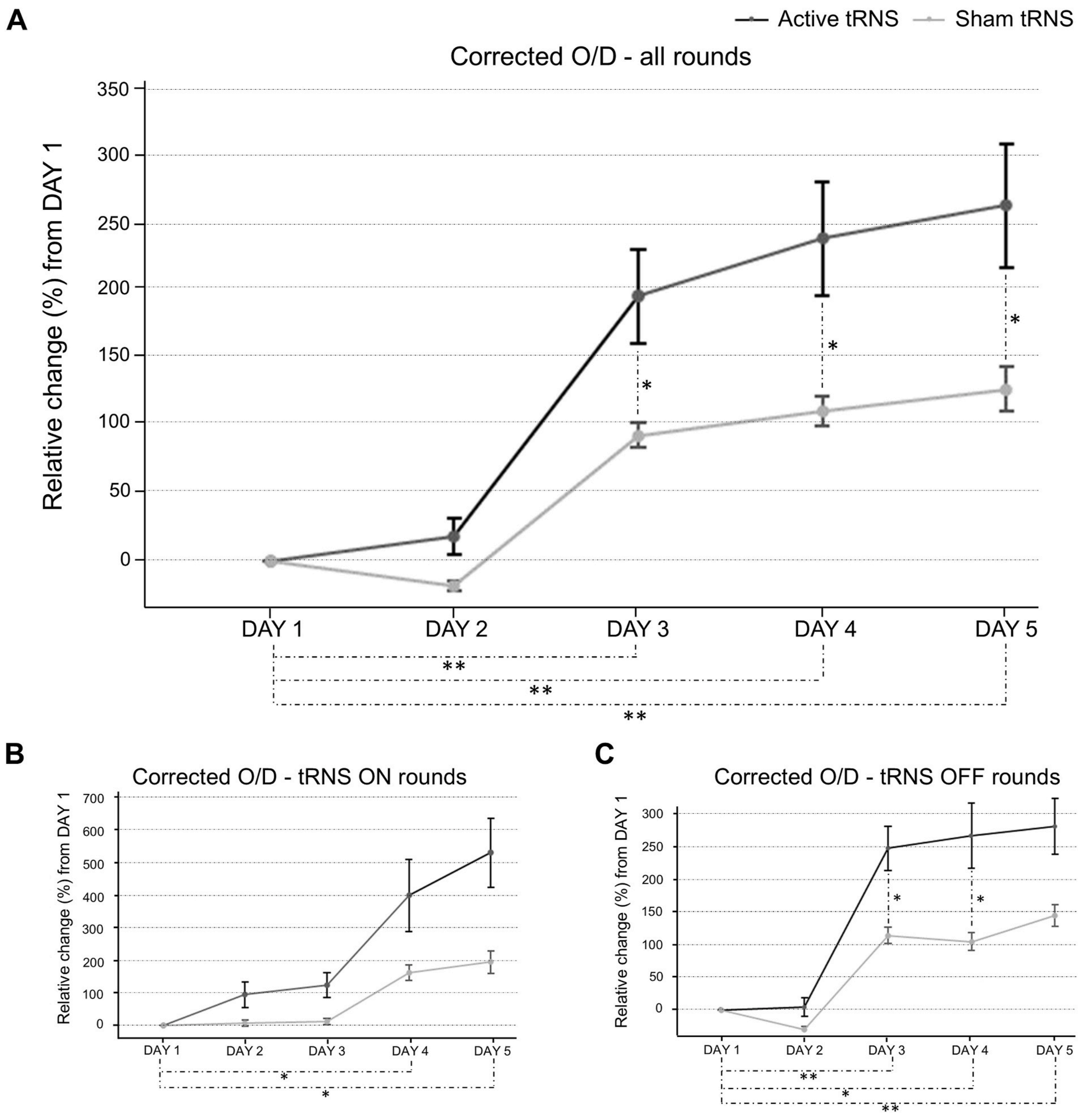


Fig. 3. Graphical representation of the training progression for both Active-tRNS and Sham-tRNS groups. Analysis of the corrected O/D ratio revealed a significant difference between the two experimental groups. Active-tRNS participants had a significantly higher performance compared to Sham-tRNS on the 3rd, 4th, and 5th day of training **(A)**. The analysis of game progression between rounds with the tRNS ON showed a significantly better performance on days 4 and 5 compared to day 1, with no difference between groups **(B)**. Conversely, the analysis conducted with the tRNS OFF highlighted a significant difference in performance between groups, with a higher corrected O/D ratio on days 3 and 4 compared to day 1 in the Active-tRNS group compared to the Sham-tRNS **(C)** (* = p < .05; ** = p < .001).

significant main effect of the *Task Performance* factor ($F_{(1.13,\ 22.74)}$ = 13.04, p = .001, η^2 = .41) and both Active-tRNS and Sham-tRNS groups improved test performance at T1 and T2 compared to T0 (p = .006 and p = .003 respectively). No interaction between factors was observed.

The aim course task analysis (Fig. 4C) showed a significant main effect of the *Task Performance* factor ($F_{(1.32,\ 26.44)}$ = 178.67, p < .001, η^2 = .89). Both the Active-tRNS and Sham-tRNS groups completed the game path faster at T1 and at T2 compared to T0 (both p < .001). There was no significant interaction between the factors. The data for both the Active-tRNS and Sham-tRNS groups are presented in Table 2 for reference.

3.3. *Cognitive assessment results*

The preliminary analysis indicated that there was no statistically significant difference between the groups in terms of cognitive task performance at T0 (p > .05). For the analysis between timepoints, non-parametric Friedman tests were employed on the raw data for all cognitive tasks, as the data showed significant deviation from normality (p < .05, Shapiro-Wilk test). Dunn's pairwise post-hoc tests were conducted, with the Friedman test yielding a statistically significant result. This was followed by Bonferroni correction for multiple comparisons.

The statistical analysis of Visual Search accuracy revealed a significant main effect of the *Task Performance* factor (χ^2 (2) = 22.04, p < .001, W = .50). Participants' accuracy was higher at T2 compared to T0 (p < .001). The Visual Search reaction time analysis showed a significant

Table 1
Training performance. Relative change (%) in the corrected O/D ratio performance from baseline (DAY 1). The asterisk indicates a statistically significant higher corrected O/D for the Active-tRNS group in comparison to the Sham-tRNS group (* = p < .05).

Training performance					
	DAY 1	**DAY 2**	**DAY 3**	**DAY 4**	**DAY 5**
Corrected O/D					
Active-tRNS (Mean ± SE)	0	17,5 (±12,8)	192,1 (±34,5)*	233,9 (±41,4)*	257,9 (±45,3)*
Sham-tRNS (Mean ± SE)	0	−17,8 (±3,4)	91,0 (±8,9)	109,2 (±10,8)	124,5 (±16,2)
Corrected O/D - tRNS ON					
Active-tRNS (Mean ± SE)	0	95,6 (±39,8)	125,5 (±38,4)	399,7 (±110,9)	531,3 (±106,1)
Sham-tRNS (Mean ± SE)	0	7,4 (±9,8)	13,1 (±10,4)	162,2 (±24,2)	195,2 (±34,1)
Corrected O/D - tRNS OFF					
Active-tRNS (Mean ± SE)	0	3,6 (±12,8)	216,3 (±29,9)*	233,3 (±43,5)*	245,6 (±37,3)
Sham-tRNS (Mean ± SE)	0	−26,1 (±3,9)	99,4 (±10,8)	91,5 (±11,6)	126,8 (±14,4)

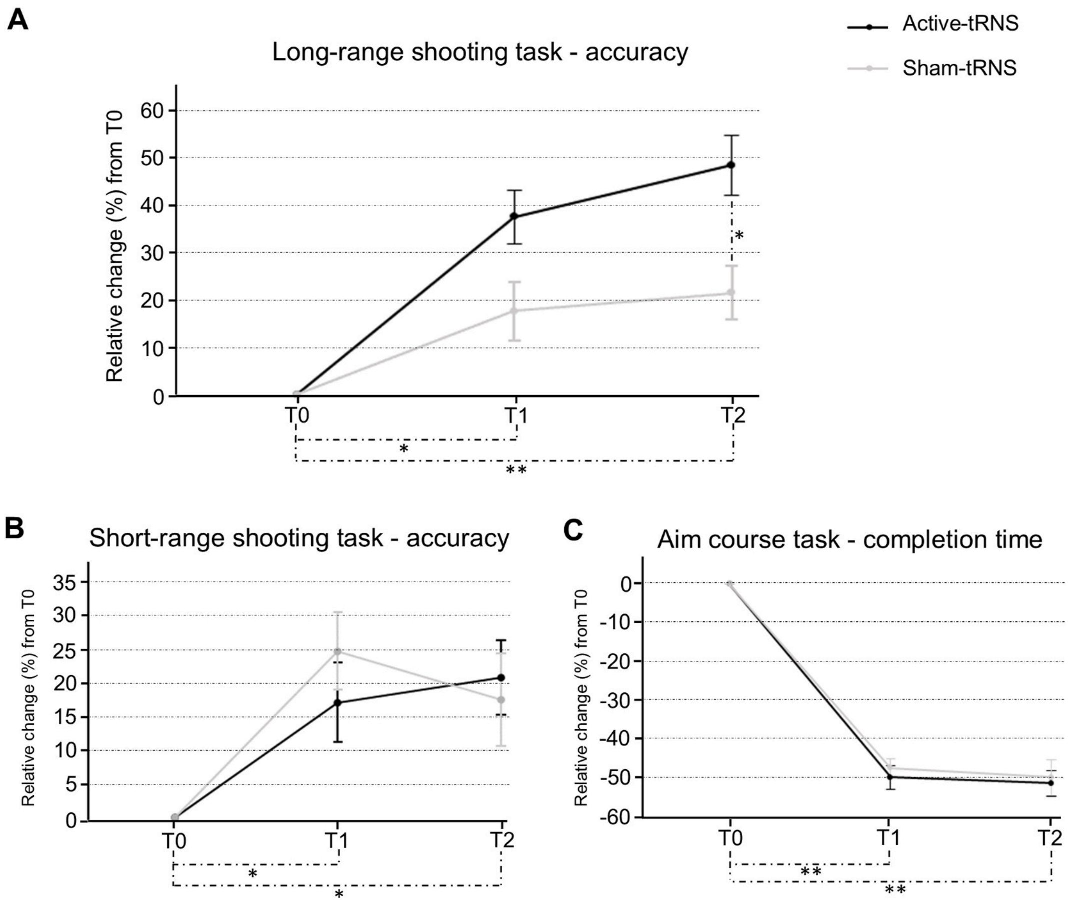


Fig. 4. Graphical representations of the significant effects observed at the shooting assessment. The analysis of the long-range shooting task showed a significant interaction between the *Task Performance* and *Group* factors. Specifically, at T2, the Active-tRNS group demonstrated significantly higher accuracy compared to the Sham-tRNS group **(A)**. In the short-range shooting task, both groups exhibited significantly higher accuracy at T1 and T2 compared to T0 **(B)**. Lastly, in the aim course task both groups experienced a reduction in completion time at T1 and T2 compared to T0 **(C)**. (* = p < .05; ** = p < .001).

main effect of the *Task Performance* factor (χ^2 (2) = 17.18, p < .001, W = .39), indicating a slower reaction time to the task at T1 and at T2 compared to T0 (p = .020 and p < .001 respectively). In the analysis of X target accuracy in the Attentional Blink task, a significant main effect of the *Task Performance* factor was observed (χ^2 (2) = 8.02, p = .018, W = .18). Participants' performance was higher at T1 compared to T0 (p = .039). With regard to the SRTT and the UFOV tasks, no significant change was observed (p > .05 in all test conducted). The analysis of the data revealed no statistically significant interaction between factors. Fig. S2 illustrates the percentage changes observed at T1 and T2 in comparison to T0, in order to more clearly demonstrate the change in cognitive task performance from the baseline.

3.4. *Cybersickness and stimulation discomfort results*

A gradual decrease in cybersickness symptoms was observed throughout the training period (Fig. 5). The Mauchly's test on SSQ revealed a violation of sphericity in the nausea (X^2 (9) = 18,23, p = .033; Greenhouse-Geisser correction ε = .664), in the oculomotor disturbance (X^2 (9) = 19.27, p = .023; Greenhouse-Geisser correction ε = .639) in the disorientation (X^2 (9) = 36.68, p < .001; Greenhouse-Geisser correction ε = .578) subscales and in the total score (X^2 (9) = 25.35,

Table 2

Shooting assessment performance. Relative change (%) in shooting task performance from baseline (T0). The asterisk indicates a statistically significant higher level of task performance for the Active-tRNS group in comparison to the Sham-tRNS group (* = p < .05).

Shooting assessment performance			
	T0	**T1**	**T2**
Long-range shooting task - Accuracy			
Active-tRNS (Mean ± SE)	0	36,3 (±5,5)	20,7 (±6,1)*
Sham-tRNS (Mean ± SE)	0	15,8 (±6,6)	17,4 (±6,5)
Short-range shooting task - Accuracy			
Active-tRNS (Mean ± SE)	0	17,0 (±5,9)	20,7 (±5,5)
Sham-tRNS (Mean ± SE)	0	24,6 (±5,7)	17,4 (±6,8)
Aim course task - Completion time			
Active-tRNS (Mean ± SE)	0	−50,0 (±3,1)	−51,4 (±3,2)
Sham-tRNS (Mean ± SE)	0	−47,5 (±2,3)	−50,0 (±4,5)

p = .003; Greenhouse-Geisser correction ε = .615). The analysis of the nausea subscale revealed a significant main effect of the *Score* factor ($F_{(2.65,\ 53.11)} = 9.61$, $p < .001$, $\eta^2 = .32$). Nausea was significantly lower on day 5 compared to day 1 (p = .004). The analysis of the oculomotor disturbance subscale highlighted a significant main effect of the *Score* factor ($F_{(2.55,\ 51.16)} = 5.81$, $p = .003$, $\eta^2 = .22$) with significantly lower symptoms on day 5 compared to day 1 of the training (p = .020). The analysis showed a significant main effect of the *Score* factor on disorientation ($F_{(2.31,\ 46.20)} = 6.06$, $p = .003$, $\eta^2 = .23$). Symptoms were significantly relieved on day 5 compared to day 1 (p < .05). Additionally, a significant main effect of the *Score* factor was found for the SSQ total score ($F_{(2.45,\ 49.16)} = 9.24$, $p < .001$, $\eta^2 = .31$) with significantly less symptomatology on day 5 compared to day 1 (p = .006) No interaction between the *Score* and *Group* factors was found in any of the analyses.

Regarding tRNS discomfort, 81.8% of the sample (18 out of 22 participants; 2 females, 16 males) experienced only mild side effects such as skin redness and itching, and no serious side effects were reported. No difference in side effects was noted between Active-tRNS and Sham-tRNS (10 and 8 participants; 1 female, 9 males and 1 female, 7 males respectively).

4. Discussion

The study originally addresses both the online and the long-term after effects of hf-tRNS on the performance in an individualized five-days VR-FPS training. The performance of two groups of young healthy subjects undergoing either real or sham stimulation was compared (Active-tRNS and Sham-tRNS, respectively), by analyzing their in-game performance, shooting skills and cognitive abilities modifications. Hf-tRNS was optimized to target a visuo-motor brain network, which is highly recruited during an FPS game (Momi et al., 2021). Our primary hypothesis was that the real stimulation would accelerate the learning curve of VR-FPS skills and enhance the effectiveness of the training program. A secondary goal was to investigate the influence of stimulation on game-related shooting abilities, with the hypothesis that these would be superior in the Active-tRNS group. Additionally, we examined the generalizability of the training or stimulation on additional cognitive functions, comparing these abilities with baseline measurements to identify patterns of change between groups over time. In general, the intervention was well tolerated and participants reported only mild and transient side effects due to the tRNS (skin redness and itching). Participants reported symptoms of cybersickness both during and after the sessions, which then decreased over the course of the training period.

A personalized training based on proficiency can help participants in optimizing their efforts by providing feedback on performance and directing behavior toward specific goals, thereby accelerating learning, with positive translational implications for everyday skills (Mishra, Anguera, & Gazzaley, 2016; Walkington & Bernacki, 2020). This process is analogous to the way students learn at school, allowing them to

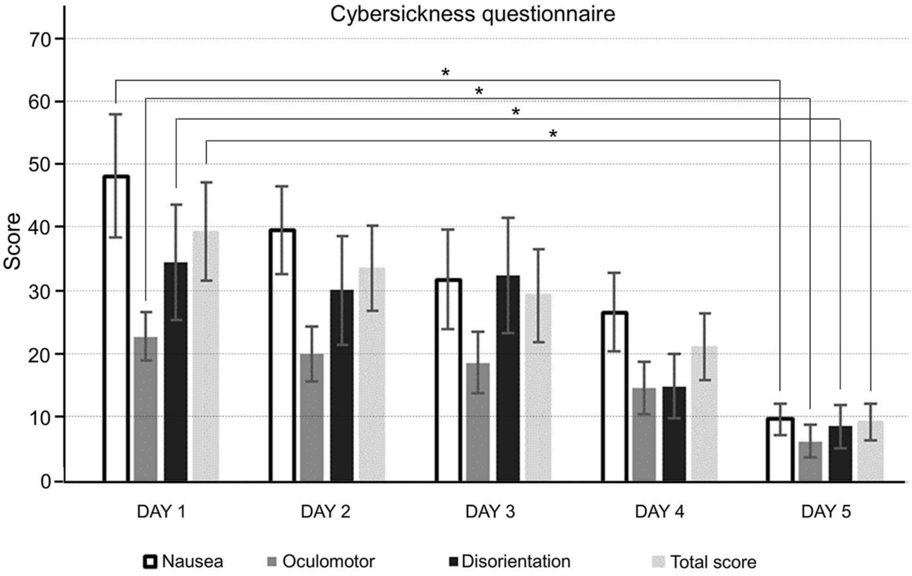


Fig. 5. Graph depicting the significant effect observed in the SSQ questionnaire. On the day 5 of training both groups reported significantly lower symptoms compared to day 1. No significant difference in symptomatology was observed between the Active-tRNS and Sham-tRNS groups (* = p < .05).

progressively overcome successive gaps for optimal learning (Fergus et al., 2022). Similarly, surgeons can acquire superior fine motor skills when exposed to an individualized VR training program that gradually increases the difficulty of simulated surgery (Gallagher et al., 2005). A recent study found that young healthy participants assigned to a personalized FPS game outperformed those assigned to a free-roaming game (Neri et al., 2021).

To individualize the training of the present study, the O/D ratio was constantly monitored, and the game difficulty parameters were adjusted according to performance and a comparison was made between the learning curves of the Active-tRNS and Sham-tRNS groups (Table 1 and Fig. 3). Both groups showed an equivalent in-game ability on the first day of the training, maintaining it on the second day. However, on the third day of training, the Active-tRNS group began to outperform the Sham-tRNS group, and this difference was maintained and even increased until the end of the training. It seems plausible that participants in the Active-tRNS group displayed greater confidence in the game environment and in operating with commands, allowing them to rapidly master the game tasks. This enabled them to successfully overcome new challenging situations with fewer teammates and more enemies. In contrast, the Sham-tRNS group exhibited a different learning curve: participants who underwent placebo stimulation may have required additional practice time to achieve the same level of performance as the Active-tRNS group.

Additionally, the study revealed a significant difference in O/D performance pattern between the tRNS ON and tRNS OFF rounds. Specifically, while the two groups exhibited comparable performance during the round with tRNS ON, the Active-tRNS group showed a higher O/D ratio than the Sham-tRNS group during tRNS OFF rounds, thereby indicating a beneficial after-effect of the stimulation over the visuomotor network. Literature reports that tRNS has a strong after-effect on accuracy abilities in memory (Murphy et al., 2020) and in motor (Laczó, Antal, Rothkegel, & Paulus, 2014) tasks, with behavioral gains lasting up to 5 months after the stimulation treatment (Harris, Eng, Miller, & Dawson, 2009). Similar to other types of tES (Santarnecchi et al., 2014), tRNS may enhance the signal-to-noise ratio at the neuronal network level, that is more easily observable after the end of stimulation and may last for a prolonged period (Brancucci et al., 2023). However, according with the Hebbian plasticity concept, providing stimulation during task learning appears to be crucial for exerting a long-lasting behavioral after-effect. Accordingly, a study by Pirulli et al. (2013) demonstrated that tRNS improves learning only when provided during training, not when applied before a learning task (Pirulli et al., 2013).

A large effect size for the training factor was found, suggesting that the training itself had a substantial impact on O/D ratio, with a significant portion of the variance in performance explained by the individualized training intervention. In contrast, the effect size for the difference between groups (Active-tRNS vs. Sham-tRNS) was smaller, indicating a moderate effect. Although the Active-tRNS group outperformed the Sham-tRNS group in training performance, the difference between the groups was less pronounced. Nevertheless, the finding that the Active-tRNS group showed superior performance aligns with our hypothesis that the stimulation would enhance training outcomes. The application of hf-tRNS over the visuomotor network can be utilized in a healthy population, including both FPS amateur and professional players for entertainment purposes or to facilitate learning in preparation for an e-sport tournament. However, this raises significant ethical concerns, particularly in relation to fairness, accessibility and the potential for creating disparities in competitive environments.

Regarding the shooting abilities assessment (Table 2 and Fig. 4), both groups showed significantly higher performance on the short-range shooting task at T1 and at T2, whereas on the long-range shooting task at T2 the Active-tRNS group showed a superior performance than the Sham-tRNS group. The difference in learning curves for shooting at distant enemies may be related to this result. Proficiency of the Active-tRNS participants in shooting at a distance can significantly improve FPS performance and the O/D ratio. This skill enables players to protect their avatar from potentially critical shots when enemies are nearby, as well as allowing them to retreat to a secure location for recovery and to engage other bots.

The results demonstrated that cognitive function benefits were observed following VR-FPS training with an approximate duration of 400 min. Furthermore, these benefits were sustained for up to one week (Fig. S2). Specifically, higher performance was found on tasks requiring attentional resources recovery and visuospatial attention resources. The findings were consistent with previous outcomes, which showed that playing videogames lead to improvements in visual attention and visuospatial abilities (Castel et al., 2005; Green & Bavelier, 2003b; Greenfield, deWinstanley, Kilpatrick, & Kaye, 1994; Momi et al., 2018; Neri et al., 2021). The personalized VR-FPS videogame can promote mechanisms of neuroplasticity governing the attentional function, and consequently enhance cognitive abilities and improve neural efficiency (Jeun, Nam, Lee, & Park, 2022). No change in sensorimotor reaction time was registered in the SRTT and a significant slower reaction time was found in the visual search task at the end of the training. In our hypothesis, the VR-FPS training might have caused a general change of participants' behavior that seems independent from the stimulation protocol, with a significant amelioration of the accuracy, with a mild increase of reaction time.

The changes on cognitive abilities are observed in both groups, regardless of the stimulation received. Thus, as evidenced in the extant literature, the effects of the tRNS seems to remain task-specific and may not generalize across different cognitive abilities. For example, studies have demonstrated that tRNS can enhance motor and cognitive functions, such as reaction times, in tasks where the brain regions stimulated are directly involved in the task demands (Jooss et al., 2019; Romanska, Rezlescu, Susilo, Duchaine, & Banissy, 2015) Therefore, the impact on cognitive abilities observed in this study appears to be directly linked to the FPS-VR training. A recent review has suggested that VR training may offer benefits in the context of cognitive impairment, with the potential to enhance cognitive abilities to a greater extent than traditional cognitive intervention (Moulaei, Sharifi, Bahaadinbeigy, & Dinari, 2024). This is particularly the case in patients diagnosed with neurodegenerative disorders (Serino et al., 2017; Thapa et al., 2020) and post-stroke patients (Lin, Ren, & Lu, 2023). The integration of tRNS within an individualized VR training for these patients may prove advantageous in enhancing the efficacy of VR environments on trained activity. Furthermore, the training may be useful for patients with impaired attentional abilities, such as those with ADHD who may exhibit deficits in reaction time and accuracy (Gualtieri & Johnson, 2006).

Finally, it takes approximately four days of training (around 400 min) for participants to fully adapt to a VR environment and significantly reduce cybersickness symptoms. It should be noted, however, that the device in question is only capable of a refresh rate of 90 Hz and recent findings have indicated that devices which are capable of supporting a refresh rate above 120 Hz have been shown to have a significant impact on the reduction of cyber sickness symptoms (Wang et al., 2023). However, no significant difference was found between the groups, indicating that tRNS did not have an effect on the cybersickness symptoms of participants who were new to the VR environment.

5. Limitations and future directions

While the current study provides valuable insights into the effects of tRNS on VR-based FPS training, several limitations should be acknowledged. First, the sample size in our study was relatively small and included only young students, which may limit the generalizability of our findings. A further limitation is the gender imbalance in our sample, with the majority of participants being male. This reflects the well-established gender differences in gaming preferences and performance, but this imbalance may limit the generalizability of our findings to females. Future research should aim to replicate these results with larger and more diverse participants to ensure the robustness of the conclusions and to better understand individual differences in response to tRNS.

Second, while our study focused on tRNS as the stimulation protocol, other NIBS techniques, such as transcranial direct current stimulation (tDCS) or transcranial magnetic stimulation (TMS) could provide additional insights. Comparing the effects of these different stimulation methods could help identify the most effective approaches for enhancing performance in VR training environments.

Furthermore, the duration of the training in our study was relatively short. Longer training periods may allow for more sustained effects and a clearer understanding of how tRNS influences long-term learning and performance. Future studies could explore whether prolonged exposure to VR training with brain stimulation leads to greater and more lasting in-game and cognitive benefits. Moreover, the effects were only assessed one week after the conclusion of the training period. However, further follow-up measurements may provide insight into the long-term durability of the observed effects.

While findings provide promising evidence for the use of tRNS in enhancing VR-based FPS training, they also raise important questions about the variability of stimulation effects across different contexts. Future research should further investigate the optimal conditions for brain stimulation in VR environments, including factors such as stimulation parameters, task complexity, and individual differences in responsiveness to tRNS (Evans, Banissy, & Charlton, 2018; Wansbrough, Tan, Vallence, & Fujiyama, 2024). Additionally, comparisons with other training modalities, such as traditional video game or physical exercises, could help clarify the specific advantages of tRNS in VR-based skill acquisition.

Future investigations could explore two potential approaches to reduce the onset of cybersickness and improve the user experience in VR environments. (i): increase the frame rate of the VR device: increasing the frame rate could reduce visual latency and enhance the overall fluidity of the VR experience, which may help alleviate symptoms of cybersickness. A higher frame rate improves the synchronization between visual and sensory feedback, thereby reducing the likelihood of discomfort and enhancing the realism of the immersive experience (Wang et al., 2023). However, VR devices with a high frame rate tend to be more expensive and may not be accessible to everyone due to their high cost. (ii): stimulation to the vestibular cortex: providing targeted stimulation to the vestibular cortex during the tutorial phase of training, when participants are most susceptible to vestibular symptoms, may assist in reducing the habituation period and minimize the onset of cybersickness. Recent studies have demonstrated that specific frequencies delivered via transcranial alternating current stimulation (tACS) may have a positive impact on mitigating symptoms of cybersickness (Rossi et al., 2023).

In summary, while our study shows that tRNS of an ad-hoc visuomotor network may improve individualized VR training, future research addressing these limitations and expanding the scope of investigation will be critical to fully uncover the potential of these interventions in both healthy and clinical populations.

6. Conclusions

The administration of hf-tRNS to an ad-hoc visuo-motor network markedly accelerated the acquisition of gaming skills and enhanced shooting abilities of healthy participants over the course of a five-day personalized training program using a VR-FPS game. Additionally, it was demonstrated that participation in an individualized VR-FPS training game has a significant impact on attentional and visuospatial abilities. These findings have the potential to inform the development of interventions for both healthy individuals and patients with attention and visuo-spatial deficits.

CRediT authorship contribution statement

Francesco Neri: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jacopo Della Toffola:** Investigation, Formal analysis. **Alberto Benelli:** Methodology. **Francesco Lomi:** Methodology. **Alessandra Cinti:** Methodology. **Sara Romanella:** Software, Methodology. **Alessandro Giannotta:** Investigation. **Simone Rossi:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Methodology. **Emiliano Santarnecchi:** Writing – review & editing, Writing – original draft, Validation, Supervision, Methodology, Funding acquisition, Data curation, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.chb.2024.108537.

Data availability

Data will be made available on request.

References

Anguera, J. A., Boccanfuso, J., Rintoul, J. L., Al-Hashimi, O., Faraji, F., Janowich, J., et al. (2013). Video game training enhances cognitive control in older adults. *Nature, 501*, 97–101. https://doi.org/10.1038/nature12486

Antal, A., & Herrmann, C. S. (2016). Transcranial alternating current and random noise stimulation: Possible mechanisms. *Neural Plasticity, 2016*, Article 3616807. https://doi.org/10.1155/2016/3616807

Basak, C., Boot, W. R., Voss, M. W., & Kramer, A. F. (2008). Can training in a real-time strategy video game attenuate cognitive decline in older adults? *Psychology and Aging, 23*, 765–777. https://doi.org/10.1037/a0013494

Battelli, L., Pergher, V., Min, O., Gardiner, L., Van Hulle, M., & Santarnecchi, E. (2022). Delayed long term impact of working memory training coupled with tRNS on near- and far-transfer cognitive tasks. *Journal of Vision, 22*, 4286. https://doi.org/10.1167/jov.22.14.4286

Bavelier, D., Green, C. S., Pouget, A., & Schrater, P. (2012). Brain plasticity through the life span: Learning to learn and action video games. *Annual Review of Neuroscience, 35*, 391–416. https://doi.org/10.1146/annurev-neuro-060909-152832

Bediou, B., Adams, D. M., Mayer, R. E., Tipton, E., Green, C. S., & Bavelier, D. (2018). Meta-analysis of action video game impact on perceptual, attentional, and cognitive skills. *Psychological Bulletin, 144*, 77–110. https://doi.org/10.1037/bul0000130

Brancucci, A., Rivolta, D., Nitsche, M. A., & Manippa, V. (2023). The effects of transcranial random noise stimulation on motor function: A comprehensive review of the literature. *Physiology & Behavior, 261*, Article 114073. https://doi.org/10.1016/j.physbeh.2023.114073

Castel, A. D., Pratt, J., & Drummond, E. (2005). The effects of action video game experience on the time course of inhibition of return and the efficiency of visual search. *Acta Psychologica, 119*, 217–230. https://doi.org/10.1016/j.actpsy.2005.02.004

Chaieb, L., Antal, A., & Paulus, W. (2015). Transcranial random noise stimulation-induced plasticity is NMDA-receptor independent but sodium-channel blocker and benzodiazepines sensitive. *Frontiers in Neuroscience, 9*, 125. https://doi.org/10.3389/fnins.2015.00125

Chenot, Q., Hamery, C., Lepron, E., Besson, P., De Boissezon, X., Perrey, S., et al. (2022). Performance after training in a complex cognitive task is enhanced by high-definition transcranial random noise stimulation. *Scientific Reports, 12*, 4618. https://doi.org/10.1038/s41598-022-08545-x

Colzato, L. S., van Leeuwen, P. J. A., van den Wildenberg, W. P. M., & Hommel, B. (2010). DOOM'd to switch: Superior cognitive flexibility in players of first person shooter games. *Frontiers in Psychology, 1*. https://doi.org/10.3389/fpsyg.2010.00008

Contemori, G., Trotter, Y., Cottereau, B. R., & Maniglia, M. (2019). tRNS boosts perceptual learning in peripheral vision. *Neuropsychologia, 125*, 129–136. https://doi.org/10.1016/j.neuropsychologia.2019.02.001

Contò, F., Edwards, G., Tyler, S., Parrott, D., Grossman, E., & Battelli, L. (2021). Attention network modulation via tRNS correlates with attention gain. *Elife, 10*, Article e63782. https://doi.org/10.7554/eLife.63782

Evans, C., Banissy, M. J., & Charlton, R. A. (2018). The efficacy of transcranial random noise stimulation (tRNS) on mood may depend on individual differences including age and trait mood. *Clin Neurophysiol Off J Int Fed Clin Neurophysiol, 129*, 1201–1208. https://doi.org/10.1016/j.clinph.2018.03.012

Fergus, S., & Petrick Smith, C. (2022). Characteristics of proficiency-based learning and their impacts on math anxiety in the middle grades. *RMLE Online, 45*, 1–19. https://doi.org/10.1080/19404476.2022.2045810

Fertonani, A., Ferrari, C., & Miniussi, C. (2015). What do you feel if I apply transcranial electric stimulation? Safety, sensations and secondary induced effects. *Clinical Neurophysiology, 126*, 2181–2188. https://doi.org/10.1016/j.clinph.2015.03.015

Fertonani, A., Pirulli, C., & Miniussi, C. (2011). Random noise stimulation improves neuroplasticity in perceptual learning. *Journal of Neuroscience, 31*, Article 15416. https://doi.org/10.1523/JNEUROSCI.2002-11.2011

Gallagher, A. G., Ritter, E. M., Champion, H., Higgins, G., Fried, M. P., Moses, G., et al. (2005). Virtual reality simulation for the operating room. *Annals of Surgery, 241*, 364–372. https://doi.org/10.1097/01.sla.0000151982.85062.80

Garrido, L. E., Frías-Hiciano, M., Moreno-Jiménez, M., Cruz, G. N., García-Batista, Z. E., Guerra-Peña, K., et al. (2022). Focusing on cybersickness: Pervasiveness, latent trajectories, susceptibility, and effects on the virtual reality experience. *Virtual Reality, 26*, 1347. https://doi.org/10.1007/s10055-022-00636-4

Green, C. S., & Bavelier, D. (2003a). Action video game modifies visual selective attention. *Nature, 423*, 534–537. https://doi.org/10.1038/nature01647

Green, C. S., & Bavelier, D. (2003b). Action video game modifies visual selective attention. *Nature, 423*, 534–537. https://doi.org/10.1038/nature01647

Green, C. S., & Bavelier, D. (2004). The effect of action video game playing on the useful field of view. *Journal of Vision, 4*, 52. https://doi.org/10.1167/4.11.52

Green, C. S., & Bavelier, D. (2006a). Effect of action video games on the spatial distribution of visuospatial attention. *Journal of Experimental Psychology: Human Perception and Performance, 32*, 1465–1478. https://doi.org/10.1037/0096-1523.32.6.1465

Green, C. S., & Bavelier, D. (2006b). Effect of action video games on the spatial distribution of visuospatial attention. *Journal of Experimental Psychology: Human Perception and Performance, 32*, 1465–1478. https://doi.org/10.1037/0096-1523.32.6.1465

Green, C. S., Li, R., & Bavelier, D. (2010). Perceptual learning during action video game playing. *Top Cogn Sci, 2*, 202–216. https://doi.org/10.1111/j.1756-8765.2009.01054.x

Greenfield, P. M. (2009). Linking social change and developmental change: Shifting pathways of human development. *Developmental Psychology, 45*, 401–418. https://doi.org/10.1037/a0014726

Greenfield, P. M., deWinstanley, P., Kilpatrick, H., & Kaye, D. (1994). Action video games and informal education: Effects on strategies for dividing visual attention. *Journal of Applied Developmental Psychology, 15*, 105–123. https://doi.org/10.1016/0193-3973(94)90008-6

Gualtieri, C. T., & Johnson, L. G. (2006). Efficient allocation of attentional resources in patients with ADHD: Maturational changes from age 10 to 29. *Journal of Attention Disorders, 9*, 534–542. https://doi.org/10.1177/1087054705283758

Harris, J. E., Eng, J. J., Miller, W. C., & Dawson, A. S. (2009). A self-administered graded repetitive arm supplementary program (GRASP) improves arm function during inpatient stroke rehabilitation: A multi-site randomized controlled trial. *Stroke, 40*, 2123–2128. https://doi.org/10.1161/STROKEAHA.108.544585

Herz, M., & Rauschnabel, P. A. (2019). Understanding the diffusion of virtual reality glasses: The role of media, fashion and technology. *Technological Forecasting and Social Change, 138*, 228–242. https://doi.org/10.1016/j.techfore.2018.09.008

Hutchins, B. (2008). Signs of meta-change in second modernity: The growth of e-sport and the World Cyber Games. *New Media & Society, 10*, 851–869. https://doi.org/10.1177/1461444808096248

Jakubowska, N., Dobrowolski, P., Rutkowska, N., Skorko, M., Myśliwiec, M., Michalak, J., et al. (2021). The role of individual differences in attentional blink phenomenon and real-time-strategy game proficiency. *Heliyon, 7*, Article e06724. https://doi.org/10.1016/j.heliyon.2021.e06724

Jerdan, S. W., Grindle, M., Woerden, HC van, & Boulos, M. N. K. (2018). Head-mounted virtual reality and mental health: Critical review of current research. *JMIR Serious Games, 6*, Article e9226. https://doi.org/10.2196/games.9226

Jeun, Y. J., Nam, Y., Lee, S. A., & Park, J.-H. (2022). Effects of personalized cognitive training with the machine learning algorithm on neural efficiency in healthy younger adults. *International Journal of Environmental Research and Public Health, 19*, Article 13044. https://doi.org/10.3390/ijerph192013044

Jooss, A., Haberbosch, L., Köhn, A., Rönnefarth, M., Bathe-Peters, R., Kozarzewski, L., et al. (2019). Motor task-dependent dissociated effects of transcranial random noise stimulation in a finger-tapping task versus a go/No-go task on corticospinal excitability and task performance. *Frontiers in Neuroscience, 13*. https://doi.org/10.3389/fnins.2019.00161

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. *The International Journal of Aviation Psychology, 3*, 203–220. https://doi.org/10.1207/s15327108ijap0303_3

Kowal, M., Toth, A. J., Exton, C., & Campbell, M. J. (2018). Different cognitive abilities displayed by action video gamers and non-gamers. *Computers in Human Behavior, 88*, 255–262. https://doi.org/10.1016/j.chb.2018.07.010

Laczó, B., Antal, A., Rothkegel, H., & Paulus, W. (2014). Increasing human leg motor cortex excitability by transcranial high frequency random noise stimulation. *Restorative Neurology and Neuroscience, 32*, 403–410. https://doi.org/10.3233/RNN-130367

Lange, B. P., Wühr, P., & Schwarz, S. (2021). Of time gals and mega men: Empirical findings on gender differences in digital game genre preferences and the accuracy of respective gender stereotypes. *Frontiers in Psychology, 12*. https://doi.org/10.3389/fpsyg.2021.657430

Li, L., Chen, R., & Chen, J. (2016). Playing action video games improves visuomotor control. *Psychological Science, 27*, 1092–1108. https://doi.org/10.1177/0956797616650300

Lin, C., Ren, Y., & Lu, A. (2023). The effectiveness of virtual reality games in improving cognition, mobility, and emotion in elderly post-stroke patients: A systematic review and meta-analysis. *Neurosurgical Review, 46*, 167. https://doi.org/10.1007/s10143-023-02061-w

Liu, N., Wu, D., Wang, Y., Zhang, P., & Zhang, Y. (2023). Transcranial random noise stimulation boosts early motion perception learning rather than the later performance plateau. *Journal of Cognitive Neuroscience, 35*, 1021–1031. https://doi.org/10.1162/jocn_a_01991

Liu, M., Zhou, K., Chen, Y., Zhou, L., Bao, D., & Zhou, J. (2022). Is virtual reality training more effective than traditional physical training on balance and functional mobility in healthy older adults? A systematic review and meta-analysis. *Frontiers in Human Neuroscience, 16*, Article 843481. https://doi.org/10.3389/fnhum.2022.843481

Makarov, I., Tokmakov, M., Polyakov, P., Zyuzin, P., Martynov, M., Konoplya, O., et al. (2016). First-person shooter game for virtual reality headset with advanced multi-agent intelligent system. In *Proc. 24th ACM int. Conf. Multimed.* (pp. 735–736). Amsterdam The Netherlands: ACM. https://doi.org/10.1145/2964284.2973826.

Mishra, J., Anguera, J. A., & Gazzaley, A. (2016). Video games for neuro-cognitive optimization. *Neuron, 90*, 214–218. https://doi.org/10.1016/j.neuron.2016.04.010

Momi, D., Smeralda, C. L., Di Lorenzo, G., Neri, F., Rossi, S., Rossi, A., et al. (2021). Long-lasting connectivity changes induced by intensive first-person shooter gaming. *Brain Imaging Behav, 15*, 1518–1532. https://doi.org/10.1007/s11682-020-00350-2

Momi, D., Smeralda, C., Sprugnoli, G., Neri, F., Rossi, S., Rossi, A., et al. (2018). Thalamic morphometric changes induced by first-person action videogame training. *European Journal of Neuroscience, ejn*, Article 14272. https://doi.org/10.1111/ejn.14272

Moret, B., Donato, R., Nucci, M., Cona, G., & Campana, G. (2019). Transcranial random noise stimulation (tRNS): A wide range of frequencies is needed for increasing cortical excitability. *Scientific Reports, 9*, Article 15150. https://doi.org/10.1038/s41598-019-51553-7

Moulaei, K., Sharifi, H., Bahaadinbeigy, K., & Dinari, F. (2024). Efficacy of virtual reality-based training programs and games on the improvement of cognitive disorders in patients: A systematic review and meta-analysis. *BMC Psychiatry, 24*, 116. https://doi.org/10.1186/s12888-024-05563-z

Murphy, O. W., Hoy, K. E., Wong, D., Bailey, N. W., Fitzgerald, P. B., & Segrave, R. A. (2020). Transcranial random noise stimulation is more effective than transcranial direct current stimulation for enhancing working memory in healthy individuals: Behavioural and electrophysiological evidence. *Brain Stimulation, 13*, 1370–1380. https://doi.org/10.1016/j.brs.2020.07.001

Neri, F., Smeralda, C. L., Momi, D., Sprugnoli, G., Menardi, A., Ferrone, S., et al. (2021). Personalized adaptive training improves performance at a professional first-person shooter action videogame. *Frontiers in Psychology, 12*.

Palma-Ruiz, J. M., Torres-Toukoumidis, A., González-Moreno, S. E., & Valles-Baca, H. G. (2022). An overview of the gaming industry across nations: Using analytics with power BI to forecast and identify key influencers. *Heliyon, 8*, Article e08959. https://doi.org/10.1016/j.heliyon.2022.e08959

Penton, T., Dixon, L., Evans, L. J., & Banissy, M. J. (2017). Emotion perception improvement following high frequency transcranial random noise stimulation of the inferior frontal cortex. *Scientific Reports, 7*, Article 11278. https://doi.org/10.1038/s41598-017-11578-2

Pirulli, C., Fertonani, A., & Miniussi, C. (2013). The role of timing in the induction of neuromodulation in perceptual learning by transcranial electric stimulation. *Brain Stimulation, 6*. https://doi.org/10.1016/j.brs.2012.12.005

Popescu, T., Krause, B., Terhune, D. B., Twose, O., Page, T., Humphreys, G., et al. (2016). Transcranial random noise stimulation mitigates increased difficulty in an arithmetic learning task. *Neuropsychologia, 81*, 255–264. https://doi.org/10.1016/j.neuropsychologia.2015.12.028

Potok, W., van der Groen, O., Bächinger, M., Edwards, D., & Wenderoth, N. (2021). Transcranial random noise stimulation modulates neural processing of sensory and motor circuits, from potential cellular mechanisms to behavior: A scoping review. *eNeuro 2022;9:ENEURO.0248-21*. https://doi.org/10.1523/ENEURO.0248-21.2021

Radhakrishnan, U., Chinello, F., & Koumaditis, K. (2023). Investigating the effectiveness of immersive VR skill training and its link to physiological arousal. *Virtual Reality, 27*, 1091–1115. https://doi.org/10.1007/s10055-022-00699-3

Remedios, L., Mabil, P., Flores-Hernández, J., Torres-Ramírez, O., Huidobro, N., Castro, G., et al. (2019). Effects of short-term random noise electrical stimulation on dissociated pyramidal neurons from the cerebral cortex. *Neuroscience, 404*, 371–386. https://doi.org/10.1016/j.neuroscience.2019.01.035

Roettl, J., & Terlutter, R. (2018). The same video game in 2D, 3D or virtual reality – how does technology impact game evaluation and brand placements? *PLoS One, 13*, Article e0200724. https://doi.org/10.1371/journal.pone.0200724

Romanska, A., Rezlescu, C., Susilo, T., Duchaine, B., & Banissy, M. J. (2015). High-frequency transcranial random noise stimulation enhances perception of facial identity. *Cerebral Cortex, 25*, 4334–4340. https://doi.org/10.1093/cercor/bhv016

Rossi, S., Cinti, A., Viberti, F., Benelli, A., Neri, F., De Monte, D., et al. (2023). Frequency-dependent tuning of the human vestibular "sixth sense" by transcranial oscillatory currents. *Clin Neurophysiol Off J Int Fed Clin Neurophysiol, 153*, 123–132. https://doi.org/10.1016/j.clinph.2023.06.013

Santarnecchi, E., Feurra, M., Barneschi, F., Acampa, M., Bianco, G., Cioncoloni, D., et al. (2014). Time course of corticospinal excitability and autonomic function interplay during and following monopolar tDCS. *Frontiers in Psychiatry, 5*, 86. https://doi.org/10.3389/fpsyt.2014.00086

Saturnino, G. B., Puonti, O., Nielsen, J. D., Antonenko, D., Madsen, K. H., & Thielscher, A. (2019). SimNIBS 2.1: A comprehensive pipeline for individualized electric field modelling for transcranial brain stimulation. In S. Makarov, M. Horner, & G. Noetscher (Eds.), *Brain hum. Body model. Comput. Hum. Model. EMBC 2018* (pp. 3–25). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-21293-3_1.

Serino, S., Pedroli, E., Tuena, C., De Leo, G., Stramba-Badiale, M., Goulene, K., et al. (2017). A novel virtual reality-based training protocol for the enhancement of the "mental frame syncing" in individuals with alzheimer's disease: A development-of-concept trial. *Frontiers in Aging Neuroscience, 9*, 240. https://doi.org/10.3389/fnagi.2017.00240

Sheehan, D. V., Lecrubier, Y., Sheehan, K. H., Amorim, P., Janavs, J., Weiller, E., et al. (1998). The mini-international neuropsychiatric Interview (M.I.N.I.): The development and validation of a structured diagnostic psychiatric interview for DSM-IV and ICD-10. *The Journal of Clinical Psychiatry, 59*. Suppl 20:22-33;quiz 34-57.

Terney, D., Chaieb, L., Moliadze, V., Antal, A., & Paulus, W. (2008). Increasing human brain excitability by transcranial high-frequency random noise stimulation. *Journal of Neuroscience, 28*, 14147–14155. https://doi.org/10.1523/JNEUROSCI.4248-08.2008

Thapa, N., Park, H. J., Yang, J.-G., Son, H., Jang, M., Lee, J., et al. (2020). The effect of a virtual reality-based intervention program on cognition in older adults with mild cognitive impairment: A randomized control trial. *Journal of Clinical Medicine, 9*, 1283. https://doi.org/10.3390/jcm9051283

Thomas Yeo, B. T., Krienen, F. M., Sepulcre, J., Sabuncu, M. R., Lashkari, D., Hollinshead, M., et al. (2011). The organization of the human cerebral cortex estimated by intrinsic functional connectivity. *Journal of Neurophysiology, 106*, 1125–1165. https://doi.org/10.1152/jn.00338.2011

Tian, F., Hua, M., Zhang, W., Li, Y., & Yang, X. (2021). Emotional arousal in 2D versus 3D virtual reality environments. *PLoS One, 16*, Article e0256211. https://doi.org/10.1371/journal.pone.0256211

Tyler, S. C., Contò, F., & Battelli, L. (2018). Rapid improvement on a temporal attention task within a single session of high-frequency transcranial random noise stimulation. *Journal of Cognitive Neuroscience, 30*, 656–666. https://doi.org/10.1162/jocn_a_01235

Vd Groen, O., Tang, M., Wenderoth, N., & Mattingley, J. (2018). Stochastic resonance enhances the rate of evidence accumulation during combined brain stimulation and perceptual decision-making. *PLoS Computational Biology, 14*, Article e1006301. https://doi.org/10.1371/journal.pcbi.1006301

Walkington, C., & Bernacki, M. L. (2020). Appraising research on personalized learning: Definitions, theoretical alignment, advancements, and future directions. *Journal of Research on Technology in Education, 52*, 235–252. https://doi.org/10.1080/15391523.2020.1747757

Wang, J., Shi, R., Zheng, W., Xie, W., Kao, D., & Liang, H.-N. (2023). Effect of frame rate on user experience, performance, and simulator sickness in virtual reality. *IEEE Trans. Visual Comput. Graphics*. https://doi.org/10.1109/TVCG.2023.3247057

Wansbrough, K., Tan, J., Vallence, A.-M., & Fujiyama, H. (2024). Recent advancements in optimising transcranial electrical stimulation: Reducing response variability through individualised stimulation. *Curr Opin Behav Sci, 56*, Article 101360. https://doi.org/10.1016/j.cobeha.2024.101360

Zhao, J., Xu, X., Jiang, H., & Ding, Y. (2020). The effectiveness of virtual reality-based technology on anatomy teaching: A meta-analysis of randomized controlled studies. *BMC Medical Education, 20*, 127. https://doi.org/10.1186/s12909-020-1994-z