Shaping oscillatory markers accounting for objective vs subjective components of time perception

Theoretical background: Time perception is a pervasive aspect of human experience. Individuals use their subjective estimates of temporal experience, while engaging in daily activities, that may or not go along with the objective passage of time[1].
Numerous models have attempted to qualify and quantify how humans process time. Among them, the pacemaker-accumulator model has been widely adopted to explain the brain's processing of event duration[2]. According to this model, an internal pacemaker emits pulses that accumulate over time to represent elapsed duration. These accumulated pulses are compared with stored reference memories to make duration judgments. Despite the popularity of this model, the neural mechanisms underlying this temporal encoding and its modulation by contextual variables remain poorly understood. Brain oscillations offer a promising foundation for implementing the pacemaker-accumulator model due to their rhythmic nature. Recently, the alpha frequency range (7-13 Hz) has been integrated into the perceptual cycle theory, which views perception as discrete processing epochs[3]. Within this framework, alpha frequency plays a crucial role in sampling visual inputs and regulating the pace of sensory processing. Faster alpha oscillations are associated with higher temporal resolution and more accurate perceptual experience[4,5]. Additionally, recent findings indicate that alpha amplitude influences the subjective interpretation of sensory signals, potentially affecting subjectively perceived time[6]. Notably, recent data demonstrate that alpha amplitude is involved in the voluntary modulation of subjective decision bias[7] and to align with temporal expectations[8]. Taken together, these findings suggest that alpha amplitude may play a role in subjective estimation of elapsed time. Yet today there is only scant or even contrasting evidence supporting this notion. Moreover, a causal demonstration of this link is missing.

Aims and Hypotheses: This project aims to investigate the neurocognitive processes underlying temporal perception. Previous studies in this area have produced conflicting results, potentially due to the confounding influence of perceptual and cognitive processes and the lack of isolation between sensory sampling components and cognitive biases. Building upon previous research demonstrating the dissociation between sensory sampling and cognitive bias in visual-spatial attention tasks, this project will employ behavioral and computational approaches [e.g., Signal Detection Theory (SDT), Drift Diffusion Model (DDM)] and EEG-informed noninvasive neurostimulation approaches.

Specifically, temporal precision (evaluated using a temporal estimation task) will be causally manipulated by means of rhythmic transcranial magnetic stimulation (TMS) aimed at speeding up or slowing down individual alpha frequency oscillations. Speeding up is expected to enhance sensory precision and thus increase the accuracy of temporal judgments, while slowing down will sort the opposite effect. On the other hand, subjective components of time perception will be manipulated by synchronizing the exact individual alpha frequency, leading to systematic temporal underestimation.

Participants, Sample Size, and Justification of the Sample Size: Despite the large effect size found in[5], when considering the proposed new line of investigation for which the directionality of the effect is unknown, we precautionarily hypothesize a medium effect size. Accordingly, using a within factor design, the power analysis estimation returned a sample size of 30, with alpha level 0.05, power 0.8, effect size f=0.25.
Tools: The research will use various tools to investigate the neural mechanisms of time perception: behavioral analysis techniques such as SDT and DDM, neurostimulation, specifically a rhythmic TMS protocol[5], and EEG analysis methods including cortical surface reconstruction [9], including time-frequency decomposition[10], IAF analysis[11], and spectral phase connectivity measures[12].

Procedure: Participants will perform a match-to-sample time and contrast estimation task adapted from the experimental paradigm developed by[13]. Briefly the participant's task is to estimate which of the two stimuli lasts longer or has more contrast. Posterior alpha oscillatory measures will be used to inform rhythmic TMS parameters including precise site of stimulation, frequency and timing. We will manipulate Pre-S1 (first presentation stimulus) or Pre-S2 (second presentation stimulus) alpha oscillations via a 5-pulse train, with the inter-pulse interval corresponding to the participant's natural IAF – thus increasing alpha-amplitude, or 1Hz faster/slower that the IAF- thus speeding up or slowing down alpha activity or finally, applying a sham stimulation, in a within subject design.

Statistical Analyses: Several statistical analyses will be conducted to examine the impact of TMS parameters on the relationship between EEG markers, behavioral indices, and SDT/DDM parameters. Group-level regression analysis will investigate the linear relationship between EEG/psychophysics, while controlling for false positives using cluster-based permutation testing. Hierarchical Bayesian estimation of DDM will be employed, followed by regression analysis to determine the relationship between oscillatory markers and DDM parameters.

Declaration of commitment to request ethical approval: The project has already been approved by the bioethics committee of the University of Bologna, on the 09/11/2022 with protocol number 0299334.

Expected Results and Implications: We expect that speeding up vs. slowing down alpha frequency will lead to better vs. worse time estimation (as well as contrast discrimination) with respect to the sham condition. On the other hand, enhancement of alpha amplitude in posterior cortex should selectively shift the individual criterion, thus shaping the subjective experience in both time and contrast tasks, while leaving objective accuracy unaltered.

References

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Plan of activities:

Project activities: 1) literature review, brainstorming and 2) piloting for refinement of methodological details; 3) data collection; 4) data analysis; 5) validation of results and interpretation; 6) participation at conferences; 7) write up of 2 papers.

Training activities: 1) computational modeling for behavioral data analysis (signal detection theory and drift diffusion model); 2) advanced TMS-EEG data analysis; 3) one-to-one weekly meetings with supervisor and 4) participation at planned lab meetings with the Consciousness group as well as with national and international partners to improve a) theoretical knowledge; b) methodological expertise c) oral and written communication skills.

Timing of activities: Literature review, brainstorming and piloting (Nov 2024 – Feb 2025). Data collection (Mar-June 2025). Data Analysis and validation (May-Sept 2025). Write-up (Sept – Nov 2025). All training activities will be carried out throughout the year.

Feasibility of the project: The project is highly feasible. All the facilities are already in place. The behavioral modeling, the EEG advanced analyses, the rhythmic TMS protocol as well as the combined online use of TMS-EEG are all expertise and activities routinely implemented by the Consciousness group.