Timing the brain and sensing the time: objective vs subjective components of time perception

Theoretical background: Time perception is a fundamental aspect of human experience. It encompasses the ability to record, estimate, and store durations of time and consists of both a subjective (the time that I feel has passed) and an objective (the time that has actually passed) dimension[1]. Numerous models have attempted to qualify and quantify how human processes 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 accumulating over time to represent elapsed duration. These accumulated pulses are compared with stored reference memories to make duration judgments. Despite the popularity of the 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.

Aims and Hypotheses: This project aims to investigate the cognitive and neural processes underlying temporal perception. Previous studies in this area have produced limited and 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)] as well as neural techniques such as Time-Frequency decomposition, Connectivity analysis, and Source estimation using electroencephalography (EEG). By clarifying the inconsistencies in the existing literature, this project aims to provide a new common framework for investigating the neurocognitive processes involved in time perception. It seeks to define time perception in neurobiological terms, incorporating multiple components of neural oscillations within the hierarchical structure of the nervous system. Temporal precision (evaluated using a temporal estimation task) will be paralleled with sensory precision (evaluated using a perceptual discrimination task), and the role of individual alpha frequency (IAF) will be examined in relation to perceptual and temporal estimation. Additionally, the project aims to explore the subjective experience of time passing and its coupling or decoupling from sensory input, particularly in longer time domains. These hypotheses are informed by the larger questions surrounding the *mystery of time* and recent findings from my research group regarding the subjective vs. objective components of sensory processing and their neural underpinnings.

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, the power analysis estimation returned a total sample size of 24, with alpha level 0.05, power 0.8, effect size f=0.25. Hence, a total of 48 participants will be recruited (24 for each study, see procedure).

Tools: The research will use various tools to investigate the neural mechanisms of time perception: behavioral analysis techniques such as SDT and DDM, and EEG analysis methods including cortical surface reconstruction[9], time-frequency decomposition[10], IAF analysis[11], and spectral phase connectivity measures[12].

Procedure: The study consists of two work packages (WP). In WP1, participants will perform a match-to-sample time- and color- estimation task adapted from the experimental paradigm developed by[13]. Briefly the participants task is to estimate either the mean color of the stimulus or its duration. In WP2, we will actively manipulate criterion shifts as participants will perform a similar temporal estimation task but with the addition of trial-by-trial prior cues, manipulating the relative probability of longer/shorter/same duration as the first stimulus. EEG data will be recorded during the tasks.

Statistical Analyses: Several statistical analyses will be conducted to examine the relationships 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:

WP1: We expect to find that detection accuracy in both color and temporal tasks will be related to IAF in posterior brain regions. Additionally, response bias, indexed by SDT and DDT parameters (criterion and starting point), will be related to alpha amplitude, suggesting a relationship between bias tendencies and increased alpha amplitude.

WP2: Introducing prior information about subsequent stimulus probability is expected to selectively affect criterion and starting point parameters, associated with fluctuations in alpha amplitude across posterior regions. However, the mechanisms of detection accuracy described in WP1 are expected to remain unaffected. The study also predicts an interaction between temporal detection duration and prior manipulation, with long-time estimates relying more heavily on prior information and reducing the importance of internal clock pacing (IAF) for task accuracy.

The findings of this study will represent a breakthrough in the understanding of the neural mechanisms underlying time perception providing unprecedented insights into the relationship between objective accuracy estimation and subjective awareness of time.

Reference (3490/3500 characters)

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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 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 (Jan-Feb 2024). Data collection WP1(Mar-May 2024). Data Analysis, validation and write-up WP1 (May-Sept 2024). Data collection WP2 (Jun-Sept 2024). Data Analysis, validation and write-up WP2 (Sept-Dec 2024). Participation at conferences (Sept-Dec 2024). All training activities will be carried out throughout the year.

Feasibility of the project: The project is highly feasible. The behavioral modeling and the EEG advanced analyses are routinely implemented by my group. The supervisor has all the required facilities and expertise needed to perform the planned experiments in the time allotted.