EEG microstate transition cost correlates with task demands

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Abstract

The ability to solve complex tasks relies on the adaptive changes occurring in the spatio-temporal organization of brain activity under different conditions. Altered flexibility in these dynamics can lead to impaired cognitive performance, manifesting for instance as difficulties in attention regulation, distraction inhibition, and behavioral adaptation. Such impairments result in decreased efficiency and increased effort in accomplishing goal-directed tasks. Therefore, developing quantitative measures that can directly assess the effort involved in these transitions using neural data is of paramount importance. In this study, we propose a framework to associate cognitive effort during the performance of tasks with electroencephalography (EEG) activation patterns. The methodology relies on the identification of discrete dynamical states (EEG microstates) and optimal transport theory. To validate the effectiveness of this framework, we apply it to a dataset collected during a spatial version of the Stroop task. Our findings reveal an increased cost linked to cognitive effort, thus confirming the framework's effectiveness in capturing and quantifying cognitive transitions. By utilizing a fully data-driven method, this research opens up fresh perspectives for physiologically describing cognitive effort within the brain.

Author Summary

In our daily lives, our brains manage various tasks with different mental demands. Yet, quantifying how much mental effort each task demands is not always straightforward. To tackle this challenge, we developed a way to measure how much cognitive effort our brains use during tasks directly from electroencephalography (EEG) data, which is one of the most used tools to non-invasively measure brain activity. Our approach involved the identification of distinct patterns of synchronized neural activity across the brain, named EEG microstates. By employing optimal transport theory, we established a framework to quantify the cost associated with cognitive transitions based on modifications in EEG microstates. This allowed us to link changes in brain activity patterns to the cognitive effort required for task performance. To validate our framework, we applied it to EEG data collected during a commonly employed cognitive task known as the Stroop task. This task is recognized for challenging us with varying levels of cognitive demand. Our analysis revealed that as the task became more demanding, there were discernible shifts in the EEG microstates. Importantly, these shifts in neural activity patterns corresponded to higher costs associated with cognitive transitions. Our approach offers a promising methodology to assess cognitive effort using neural data, contributing to our comprehension of how the brain manages and adapts to varying cognitive challenges.

Introduction

The complex activity patterns that support perception, cognition, and behavior in the healthy brain arise from the interactions of neuronal populations across various spatial and temporal scales [Liégeois et al., 2019]. At the macroscale, brain activity is characterized by spatially distributed groups of regions that exhibit temporally correlated activity and co-activate during behavioral tasks, thus acting as functional networks. Recently, it has been shown that such functional networks may reflect the long-time average of rapidly

switching metastable patterns (also called “metastable substates” or “dynamical states”), which are consistently observed with different imaging methods [Calhoun et al., 2014; Preti et al., 2017; Kringelbach et al., 2020; Rajkumar et al., 2021; Coquelet et al., 2022]. In the M/EEG literature, these patterns are termed “microstates” and are highly reproducible across studies and clustering techniques [Michel et al., 2018; Von Wegner et al., 2018; Tarailis et al., 2023].

As our environment is constantly evolving, with new stimuli and challenges emerging regularly, our brain must remain flexible and adaptable to respond effectively to these changes. A crucial component that drives such reconfiguration is “executive functioning” or “cognitive control” [Botvinick et al., 2001; Braver, 2012; Friedman et al., 2017]. This construct refers to the set of processes and mechanisms that enable goal-directed behavior in the face of changing circumstances [Banich, 2019; Miller & Cohen, 2001; Botvinick et al., 2001; Posner & Snyder, 1975]. When confronted with challenging situations, cognitive control allows the brain to regulate attention, inhibit irrelevant information, and shift cognitive resources to prioritize relevant tasks or goals [Ochsner et al., 2005].

Concurrently, it has been shown that the dynamical properties of the metastable substates during different active conditions are modulated compared with the resting state. Such adaptation has been demonstrated in a large variety of conditions such as cognitive loads [Capouskova et al., 2022], sleep-awake cycle [Deco et al., 2019], habituation of cognitive tasks [Szymula et al., 2020], and is reflected in the overall reconfiguration of functional connectivity [Kitzbichler et al., 2011; Hutchinson et al., 2013; Gonzalez-Castillo et al., 2018]. Importantly, alterations in the dynamic of brain states were found in psychiatric [Michel et al., 2018; da Cruz et al., 2020] and neurological disorders [Favaretto et al., 2022] and during normal aging [Moretto et al., 2022]. Therefore, developing quantitative measures for quantifying the cost of such reconfiguration in the brain is crucial for explaining the impairments and guiding the possible effects of therapeutic interventions [Deco et al., 2018].

In recent years, much attention has been captured by the network controllability framework for measuring the brain transition cost [Tang et al., 2018; Lynn et al., 2019]. Control theory based tools offer a mechanistic explanation for how the brain moves between cognitive states drawn from the structural network organization. In addition, control theory provides a quantitative way of computing the control cost as the amount of energy needed to steer a system along a desired trajectory. Despite its potential and broad spectrum of applications, it has some strong limitations [Tu et al., 2018; Suweis et al., 2019]. For instance, it relies on the assumption of linearity in the dynamics. However, linear models fail to capture non-linear [Friston, 2001] and higher-order [Herzog et al., 2022] phenomena ubiquitously encountered in brain dynamics. Moreover, stochasticity is not considered, but it is essential for accurately describing many aspects of brain function [Deco et al., 2009].

A promising approach for circumventing these limitations in quantifying the cost of control consists of reframing the task into a Schrödinger bridge problem [Pavon et al., 2021; Chen et al., 2021]. More specifically, given an initial and a target probability distribution, the Schrödinger bridge problem asks for the most likely path or "bridge" that connects the two probability distributions given the spontaneous stochastic dynamics of the system. The transition cost is then estimated as the Kullback-Leibler divergence, which measures distances in the probability distribution space, between the baseline trajectory and the bridge. Intuitively, it measures the cost of “transporting” one distribution into another by a stochastic process that satisfies some given constraints. Indeed, the Schrödinger bridge problem has been proven to be formally equivalent to an (entropy-regularized) optimal transport problem [Chen et al., 2016; Peyrè et al., 2019].

Recently, such an approach was applied to an fMRI dataset of participants performing several cognitive tasks [Kawakita et al., 2022]. The authors show that the transition cost from the resting condition to the various tasks varies significantly, thus proposing this approach might be suitable for describing neurophysiological data. However, the tasks were qualitatively different and difficult to compare, thus there were no strong prior expectations of the task difficulty and the expected cognitive demand. Additionally, the reliability of individual differences in task-based fMRI activity is known to be quite poor [Elliot et al., 2020], especially in the absence of long time series, as typically occurs in fMRI data, thus hindering the possibility of a subject-level analysis. Hence, in [Kawakita et al., 2022] time series data from individual subjects were

combined to create a unified meta-subject dataset. Therefore, the analysis was exploratory and the reliability of such a metric remains limited. Moreover, in many contexts of cognitive interests, fMRI is not a suitable tool to measure neural correlates of behavior. For instance, one of its primary constraints is its inherent limitation to cognitive tasks that do not involve significant physical movement. This is a notable drawback, as many cognitive processes and behaviors inherently entail motor actions.

In this work, we bridge this gap by generalizing the above method to electroencephalography (EEG) signals, which moreover measure neural activity more directly than fMRI. Specifically, we analyze an EEG dataset on participants performing a spatial Stroop task. The Stroop task is a standard experimental paradigm in cognitive psychology that investigates different aspects of cognitive control and executive functions, including selective attention, response inhibition, and interference resolution, by assessing the interference effect from conflicting stimulus features [Stroop, 1935]. In its spatial variant [Ambrosini & Vallesi, 2017; Viviani et al., 2022; Viviani et al., 2023], participants are typically presented with arrows pointing in different directions (e.g., top left or bottom right) and are asked to indicate the direction of the arrow through a spatially compatible button press. However, the pointing direction may conflict with its spatial location. For example, an arrow pointing to the top left corner might appear on the bottom right side of the screen. Typically, participants are slower and less accurate in incongruent conditions (i.e., when the spatial location of the arrow conflicts with the direction it is pointing to) than in congruent conditions (i.e., when spatial location and pointing direction coincide). This interference effect, referred to as the "Stroop effect", is believed to reflect the difficulty in suppressing the automatic processing of the spatial location of the stimulus in favor of the task-relevant information (the arrow direction), with the consequent activation of a wrong response code that then needs to be suppressed. Commonly, it is computed as the difference in the response time (RT) between incongruent and congruent trials. Cognitive control demands can be further manipulated by varying the proportion of congruency (PC), namely the proportion of congruent trials in a given task block [Visalli et al., 2022]. Indeed, in high-PC blocks, conflict is less likely, and cognitive control demands are lower, whereas, in low-PC blocks, trials are mostly incongruent, and cognitive control is more required [Bugg, 2014; Gonthier et al., 2016]. Therefore, due to our well-defined quantitative prior expectation of cognitive demands, this dataset is ideally suited for assessing the effectiveness of the proposed framework to estimate brain transition costs.

Here, we first characterize the dynamics with a microstate analysis, which reveals that different conditions modulate the distribution of microstates. Specifically, we observe a distinct topography that is more prominent during the task, while two other topographies are enhanced and reduced, respectively, solely during the presentation of incongruent stimuli. Next, we calculate the transition cost for each participant from the resting state to the various conditions. We observe a higher cost for incongruent stimuli. Importantly, this cost is significantly influenced by the level of cognitive control. Moreover, we find a correlation between variations in the cost and RTs, showing that a reduced cost is associated with improved task performance. Overall, these results highlight the value of characterizing brain dynamics and transition costs in understanding cognitive processes and offer insights into the relationship between neural activity patterns, cognitive effort, and behavioral performance.

Results

Framework for computing the control cost

In this work, we delved into an EEG dataset recently collected (see "Dataset" section; Fig. 1a). This dataset encompasses EEG recordings collected from a cohort of 44 participants during both resting and task-oriented sessions. Specifically, the task involved a spatial Stroop task designed with blocks featuring three distinct PC values (25%, 50%, and 75%) to systematically manipulate different levels of cognitive control engagement, which were characterized as High, Medium, and Low, respectively.
Consequently, this setup provided multiple pre-established levels of cognitive demand expectation.
EEG activity was characterized utilizing a microstate analysis (see "EEG microstate-based analysis" section; Fig. 1b). After identifying the most reliable templates for group maps, we proceeded to assess their occurrences and transitions in each participant during both the resting and task conditions.

Utilizing their dynamics, we derived an estimation of the control cost employing the Schrödinger bridge framework (see "Brain transition cost" section, Fig. 1c). In essence, this cost was calculated as the disparity between the spontaneous microstate dynamics during the resting phase and the bridge, which corresponds to the most likely pathway linking the distributions of microstates observed during resting and task-oriented conditions.

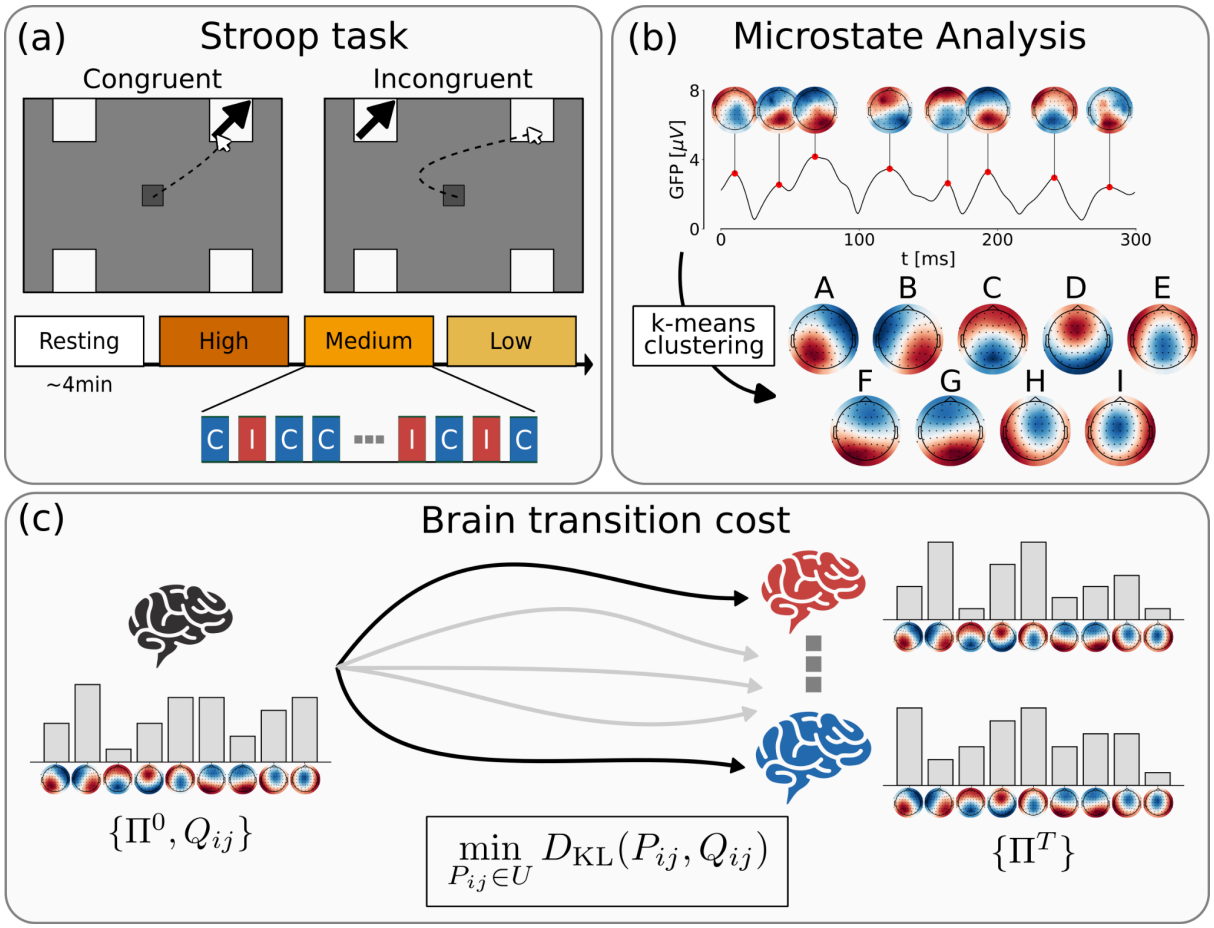

Figure 1. Summary of the framework for the computation of the brain transition cost from EEG data. *(a)* The EEG activity of 44 participants was acquired at rest and while performing a spatial Stroop task. The participants were presented either with a congruent (C) or incongruent (I) stimulus. The proportion of congruency was modulated within three blocks (Low: 75% C, 25% I; Medium: 50% C, 50% I; High: 25% C, 75% I). (*b*) EEG activity was characterized by employing a microstate analysis. The modified k-means clustering found nine most representative topologies, which we named from A to I. (*c*) Schrödinger bridge framework for computing brain transition cost. Given the microstate occurrence probability at rest (π^0) and while performing a task (π^T), the cost is computed as the Kullback-Leibler divergence between the spontaneous (resting) dynamics, described by joint probability for two consecutive steps (Q_{ij}), and the Schrödinger bridge, i.e., the most probable path that links the resting and task distribution, subject to the given constraints.

Microstate reconfiguration during task

The group-level clustering revealed nine optimal microstate classes, which explained almost 80% of the variance of the dataset (Fig. S1). Five of these group maps resembled the usual microstates template ubiquitously found in the literature [Michel et al., 2018], and we labeled them accordingly (from A to E). The remaining ones were not present in such templates but were found in our experiments, thus we labeled them arbitrarily respecting the axial symmetry (F, G and H, I) (Fig. 1b). Such templates might be specific to the cognitive control task as found in other task-related microstate analyses [Minguillon et al., 2014].

Before entering into applying the control cost framework, we needed to verify whether microstate occurrences during the task were modulated with respect to the baseline (Fig. 2). To achieve this, we utilized a mixed linear model for each microstate, incorporating congruency, control level, and their interaction as fixed factors (Tab. S1). As a dependent variable, we computed the change in the probability of occurrence across different conditions compared to the resting state. Consequently, the intercept denoted an overall modulation from the resting state to task performance. We found that microstate A is significantly suppressed during the execution of the tasks. As a tentative speculation, such depression might be related to alpha suppression or the deactivation of the default mode network. On the other hand, microstate E was more enhanced during incongruent stimuli, possibly linked to the activation of executive network nodes, while microstate F was suppressed, which could be related to the default mode network disengagement for a more demanding task condition. Instead, the remaining microstates did not show significant differences among the different conditions after correction for multiple tests (see Fig. S2, Fig. S3).

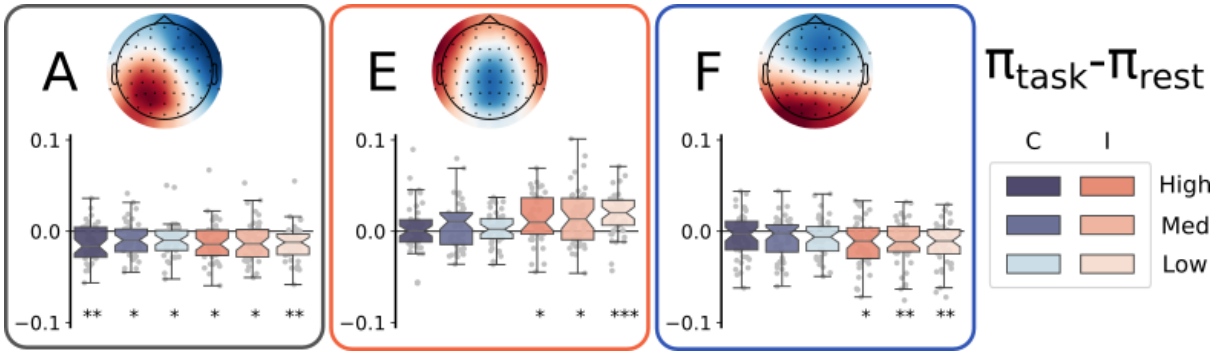

Figure 2. Microstate occurrence distinguishes tasks from resting. Microstate A is specific for resting (p(intercept)<0.001), while microstates E (p(congruency)<0.001) and F (p(congruency)=0.02) are specific for the resolution of the interference. Boxplots indicate the distribution of the difference in the probability of occurrence during each task and the resting state, obtained from 44 individuals. Blue (orange) scale represents congruent (incongruent) stimuli. The saturation of the blue (orange) scale represents the level of control demands. To assess the modulation of occurrence during each condition, we employed a linear mixed model with congruency, control level, and their interaction as fixed factors (see Sec. 3.1, Table S1). The stars correspond to the p-values of the post hoc t-tests reported in Figure S2.

Transportation cost matrix

A key quantity, that we inferred from the EEG time series and their microstates, was the transportation cost matrix (Fig. 3a). Such a matrix, in an optimal transport problem, provides information about the costs associated with transporting goods or resources from one location to another. In our framework, it defines the cost associated with increasing or decreasing the occurrence of one microstate from the source to the target distribution, and it has a clear intuition: the transportation cost is minimized along the more favorable transitions (i.e., more probable) during rest.

For each participant, the transportation cost was obtained from the joint probability distribution of co-occurrence for two consecutive steps during resting. As shown in Fig. 3b, we found that such distribution is asymmetric, indicating a preference or bias in transitioning from one state to another with respect to the opposite direction. Such asymmetric transitions indicate potential fluxes and net flows within the system, which in turn can contribute to the overall production of entropy at a macroscopic level [Lynn et al., 2021]. Therefore, our results hint at a macroscopic entropy production of the brain, even at rest. Moreover, the self-transition probabilities are quite large, indicating that the system tends to persist in its current state over time, thereby confirming the metastable nature of the microstates.

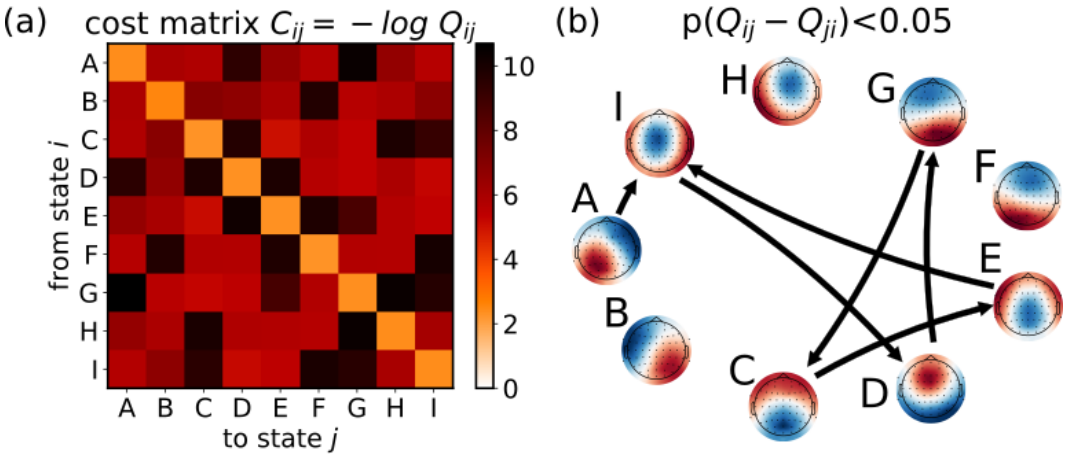

Figure 3. Estimating the transportation cost matrix from microstate joint probability of consecutive timesteps at rest. (*a*) Transportation cost matrix, averaged over the 44 participants, representing the cost for the brain to transition from state *i* to state *j*. (*b*) Network describing the transitions among microstates during resting. We show only the significant asymmetric transitions (t-test, p<0.05).

Transition cost reflects task demand

Subsequently, we investigated for each participant the costs associated with transitioning from a resting state to different conditions within the Stroop task. To quantify these costs, we utilized the Schrödinger bridge framework and calculated the associated Kullback-Leibler divergence (Fig. 4a). Our results unveiled a significant influence of both stimulus type and proportion congruency on the computed transition costs, with a marginal significance also on the interaction, as evidenced by the two-way analysis of variance (ANOVA) test (p(congruency)=0.034, p(control level)=0.024, p(congruency*control level)=0.049). To delve deeper into these effects, Bonferroni corrected post hoc t-tests were performed. We found significant differences between congruent stimuli with higher and lower proportion congruency (p<0.001). Moreover, in the case of lower proportion congruency, we found a significant difference between the two kinds of stimuli (p=0.019).

To examine the potential relationship between transition costs and subjective performance, we conducted a correlation analysis between the computed costs and reaction times (Fig. 4b; Fig. S4). Specifically, we calculated the difference in costs and reaction times between congruent and incongruent conditions, considering each level of control. We computed the Pearson correlation for each participant and subsequently applied a z-transformation. Our results revealed a significant positive correlation within this distribution (t-test, p=0.023), indicating that higher transition costs were associated with longer reaction times and potentially indicative of performance.

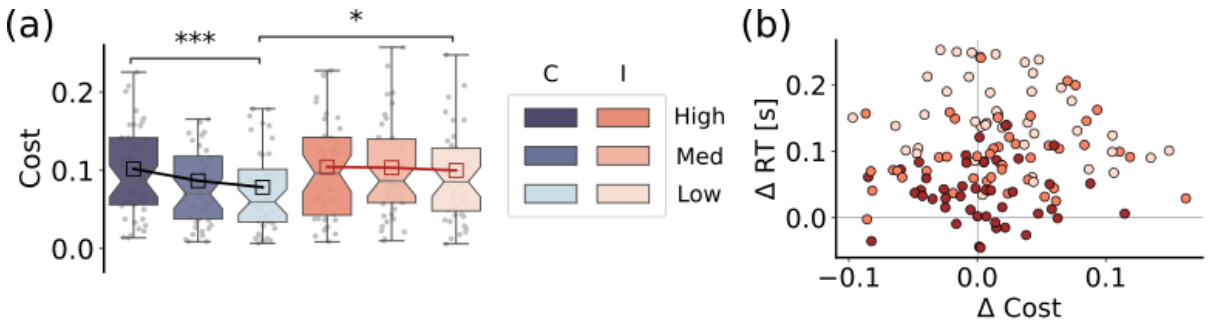

Figure 4. Brain transition cost correlates with task demand and performance. (*a*) The distribution of transition costs for each stimulus is significantly modulated by the stimulus type, that is congruent (C) vs. incongruent (I) (p(congruency)=0.034), by the level of cognitive control (high, medium, low; p(control level)=0.024) and by their interaction (p(congruency*control level)=0.049). (*b*) The increased cost from congruent to incongruent stimuli (Δ Cost) significantly correlates with the increase in reaction time (Δ RT). For each participant, we computed the (z-transformed) Pearson correlation (t-test, p=0.023).

Discussion

In this study, we have employed a stochastic control framework to measure the brain transition cost in an existing EEG dataset. Through our investigation, we have confirmed a correlation between cost and cognitive demand observed during a spatial Stroop task. To our current knowledge, this is the first application of such a framework to EEG data, thus providing a computational pipeline to quantify cognitive demand in EEG experiments.

To estimate brain transition costs from the Schrödinger bridge framework, we used a probabilistic approach that resorts to a reduction of dimensionality. A growing body of literature suggests that brain activity, across different scales, exhibits organization within a low-dimensional manifold. The trajectories of neural activity can thus be described as discrete transitions between a few metastable attractors, which capture a significant portion of the overall activity variance. In particular, the analysis of EEG activity is increasingly conducted using the microstates approach. This method reduces the recorded electrical signal into non-overlapping and distinct topographies [Michel et al., 2018; Von Wegner et al., 2018]. Although individual topographies have been associated with partial activations or deactivations of canonical resting-state networks [Custo et al., 2014; Custo et al., 2017] and specific spectral bands [Férat et al., 2022; Mikutta et al., 2023], the functional and cognitive role of the microstates has not yet been fully established [Tarailis et al., 2023].

Specifically within our dataset, we found distinct occurrences of microstates across different conditions. Notably, certain microstates differentiated between tasks and resting states, while others were specific to incongruent stimuli. Furthermore, these microstates were influenced by the (assumed) level of control within a block. Consequently, they may be linked to specific brain regions involved in inhibitory control and conflict resolution [Heidlmayr et al., 2020]. Moreover, their modulation could be associated with the dynamic reorganization of functional networks, as previously observed [Spielberg et al., 2015; Braun et al., 2015]. Confirmation of these hypotheses and further investigation into the microstates can be achieved through source localization, which will be explored in future works.

Overall, a higher cost may be related to a larger network reconfiguration. Indeed, a larger cognitive demand induces a more global alteration in brain activity, which is needed to make functional networks transiently adopt a more efficient but less economical configuration [Kitzbichler, 2011]. However, the specific mechanisms governing these shifts between states of the brain remain unclear [Lee et al., 2012; Zagha et al., 2014]. Moreover, whether such cognitive cost may represent an increase in metabolic consumption is still to be investigated [Hanh et al., 2020]. It is important to mention that in a stochastic linear setting, the Schrödinger bridge control cost is formally equivalent to the "classical" control cost (i.e., the expectation of the time integral of squared control signal) [Beghi, 1996; Chen et al., 2016; Kawakita et al., 2022], which has a clear physical interpretation.

Our approach integrates into the current literature on the brain's neural control [Ashourvan et al., 2017; Tang et al., 2018; Lynn et al., 2019; Tu et al., 2018; Suweis et al., 2019; Singleton et al., 2022; Scheid et al., 2021; Deco et al., 2019; Lee et al., 2012; Zagha et al., 2014]. The core foundation of all these models involves a metric that quantifies the amount of effort required for a dynamical system to traverse its state space across diverse conditions. The existing methodologies typically rely on the full knowledge of the underlying structural connectome and an explicit representation of the dynamics. Under the assumption of linear dynamics, it is possible to estimate this metric efficiently by utilizing an explicit analytical formula [Tang, et al., 2018; Kamiya et al., 2023]. However, these approaches overlook the intricate nonlinear characteristics of brain dynamics, and may not be computationally feasible for large networks [Tu et al., 2018]. On the contrary, to extend this framework to biophysically detailed dynamical models, extensive numerical simulations become a necessary recourse [Deco et al., 2019]. Instead, our approach offers the advantage of estimating the reconfiguration cost directly from neurophysiological recordings, eliminating the need for a structural network or mathematical modeling of the whole brain dynamics. Additionally, its flexibility allows for versatile application across various imaging techniques [Kawakita et al., 2022]. However, its applicability to EEG data holds particular importance due to its widespread usability, cost-effectiveness compared to techniques such as fMRI or MEG, and non-invasiveness compared to intracranial recordings.

It would be interesting to explore whether pathological conditions could influence the control cost. For instance, in the case of stroke, there have been documented changes in the microstates [Hao et al, 2022; Rubega et al., 2022] and, more generally, in the dynamics of metastable states [Favaretto et al., 2022]. Furthermore, different conditions may affect distinct regions of the brain, resulting in alterations across various domains [Corbetta et al., 2015]. Consequently, it is reasonable to assume that the cognitive cost will be particularly higher for tasks impaired due to specific neural alterations. Therefore, investigating individual differences in microstate transition cost in different groups (e.g., strokes), or applying it to tasks where the evaluation of cognitive demands is not known, are all interesting avenues to pursue in future research.

Materials and Methods

Dataset

We re-analyzed the continuous EEG data collected in a recent study from our lab [Tafuro et al., 2020]. In that study, we aimed to investigate the neural correlates of cognitive control in resolving the interference between competing responses. To this aim, we recorded EEG in 44 participants in a 4-min resting state session and while they performed a spatial Stroop task requiring mouse responses and comprising blocks with three PC values (25%, 50%, and 75%) to manipulate different levels of cognitive control engagement (respectively, High, Medium, and Low; Fig. 1a; see Tafuro et al., 2020, for details about the task and procedure). A standard ICA-based preprocessing was performed to correct for eye movements, blinks, and muscular activity based on scalp topography, dipole location, evoked time course, and the power spectrum of the components [Tafuro et al., 2020].

EEG microstate-based analysis

Preprocessed EEG data were further bandpass filtered (1-40 Hz), downsampled at 125 Hz, and temporally smoothed with a Gaussian kernel (5 timesteps) [Chen et al., 2021].

Microstate analyses followed the modified k-means clustering algorithm [Murray et al., 2008; Poulsen et al., 2018]. Local maximal values (peaks) of the global field power (GFP) were extracted from each EEG recording. GFP was calculated as the standard deviation of the amplitude across all channels at each time point. EEG maps at GFP peaks are reliable representations of the topographic maps because of their high signal-to-noise ratio [Koenig et al., 2002].

We randomly extracted the same number (1500) of maps from each participant, that were concatenated and subjected to clustering. The optimal number of clusters (K*=9) was determined using the cross-validation criterion, which minimizes the variance of the residual noise (see Supporting information - Text S1). The centroids of the K* clusters identify the group-specific microstate templates (Fig. 1b).

The common templates were then fitted back to the preprocessed EEG recordings. The EEG map at each time point was labeled according to the map with minimum Euclidean distance, equivalent to the highest absolute spatial correlation. Thereafter, EEG maps were converted into microstate sequences (k_t). For each EEG recording, we characterized the probability distribution of microstate occurrence (π). In addition, we compute the joint probability distribution Q_{ij} for two consecutive steps i and j during the resting period (i.e., $Q_{ij} = Prob[k_{t-1} = i;\ k_t = j]$).

Brain transition cost

To quantify the cost of transitioning from resting to task, we applied the Schrödinger bridge problem [Leonard, 2013] (Fig. 1c). We assumed that at rest the brain follows a (stochastic) baseline activity between the microstates. To reach the desired target, the brain had to modulate its dynamics. The Schrödinger bridge problem finds the most likely path linking the initial and target distribution given the prior stochastic evolution of the system by minimizing the Kullback-Leibler divergence between the two distributions, subject to the aforementioned constraints [Kawakita et al., 2022].

In mathematical terms, we defined π^0 and π^T as the initial (resting) and target (task) probability distribution. The prior evolution of the system is encoded in the joint probability distribution at rest, Q_{ij}. The transition cost could thus be quantified as

$$Cost = min_{P_{ij} \in U} KL(P_{ij}, Q_{ij}) = min_{P_{ij} \in U} - \sum_{ij} P_{ij} log Q_{ij} + \sum_{ij} P_{ij} log P_{ij} = min_{P_{ij} \in U} \sum_{ij} C_{ij} P_{ij} - H(P_{ij}),$$

where $C_{ij} = - \log Q_{ij}$ plays the role of a transportation cost matrix, $H(P_{ij})$ is the information entropy and the minimization is constrained over the matrix spaces $U = \{P_{ij} > 0 \,\&\, \sum_{ij} P_{ij} = 1 | \sum_{j} P_{ij} = \pi_j^T \,\&\, \sum_{i} P_{ij} = \pi_j^T \}$.

Indeed, the Schrödinger bridge problem can be recast as an entropy-regularized optimal transport problem [Beghi, 1996]. Intuitively, to supply the needed cognitive demand, the brain has to modulate its dynamics, which results in a modulation of microstate occurrence. In other words, the occurrence of some microstates would be enhanced, while others would be suppressed. Thus, the brain has to "transport" some mass (i.e., microstate occurrence) into another. How much mass is moved from each supply (i.e., resting) location to each demand (i.e., task) location is defined as the "transportation plan" and is encoded in the matrix P_{ij}. The transportation cost matrix C then represents the cost of transporting one unit of mass along each supply-demand pair. Solving the optimal transport problem means finding the transportation plan P_{ij} that minimizes the total cost (with an entropic regularization term) while satisfying constraints like the given initial, supply, and final, demand distributions and non-negativity constraints (i.e., ensuring that negative values are not allowed in the transportation plan).

This is a strongly convex optimization problem, therefore the existence and uniqueness of the optimal solution are guaranteed. Such an optimal solution can be iteratively determined in an efficient way using the Sinkhorn algorithm [Cuturi, 2013].

Data availability

The preprocessed data and the code that support the findings of this study are available at https://github.com/gbarzon/brain_control_cost.

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