Analysis of EEG Microstates During Execution of a Nine Hole Peg Test

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***Abstract*—EEG microstates are brief periods of time during which the brain's electrical activity remains stable. The analysis of EEG microstates can help to identify the background neuronal activity at the millisecond level. The main objective of this study is to observe changes in brain microstates by varying demand during different experiment phases, involving a fatiguing exercise. The hypothesis explored in this paper is that resting state and fine motor states involve different neural assemblies and that physical fatigue induced using a wrist dumbbell flexion/extension exercise impacts these microstates. An experiment is conducted with 5 healthy participants, exploring this. Three distinct microstates are observed during the resting state and a separate set of 3 states are observed during the Nine Hole Peg Test. Changes are assessed by utilising microstate parameters such as occurrence, coverage, duration, and global explained variance. It is found that the coverage of microstate C for resting states decreases for all the participants after the dumbbell exercise. During the fine-motor task, the coverage of microstate MS3 decreases for all participants except one. These results support the involvement of different neural assemblies, but also highlight the potential that physical fatigue can be observed and identified by assessing changes in microstate features, in this case, a parameter such as coverage.**

***Index Terms*—EEG, microstates, NHPT, Geomagic Touch.**

I. Introduction

Human movements are controlled by the Central Nervous System. Stroke is a condition where the blood supply to the brain is disrupted, resulting in oxygen starvation, brain damage and loss of function. One in six people worldwide will have a stroke in their lifetime [1]. Over three-quarters of stroke survivors report arm weakness, which makes their daily living activities difficult [2]. Understanding the neural mechanisms related to hand movements will help in effective therapy designs for stroke patients. Therapy often benefits from assessment to inform progress. The Nine Hole Peg Test (NHPT) is one of the easiest and widely used tests for measuring dexterity. A reliable outcome measure of NHPT is the time taken to complete placing nine pegs into nine holes [3]. Haptic devices have the potential to provide further performance metrics to inform on the quality of the fine motor task. We have designed haptic instruments for simulating the NHPT as detailed in earlier work [4], [5]. These studies indicated that the addition of haptic and virtual reality may introduce new cognitive demands while providing more extensive performance metrics. To explore this further, we decided to utilise the brain's microstate recording before, during, and after NHPT. Separately, we have also explored the electromyographical impact of fatigue on gross motor muscles [6] that highlighted needs to further explore neural correlates at the brain level, to understand the complete chain of events leading to mental and physical fatigue.

The concept of EEG microstates was developed by Dietrich Lehmann and his team in the late 1970s to quantify the spatio-temporal dynamics of the brain [7]. They suggested that the multichannel EEG recorded over the brain follows a stable map configuration for a short period of time. EEG microstates were called atoms of thought since they were thought to reflect individual high-level aspects of cognition and information processing [8]. Changes in the scalp electric field configuration imply changes in the distribution of underlying neural generators. This means that different microstate topographies at any time reflect the neural network activity predominating at that time [9]. The effect of fatigue on microstate intensity has been investigated and it was found that the amplitude of microstates increases when going from alert to the fatigued state [10]. Not many studies have investigated changes in EEG microstates during physical fatigue, however, changes in microstate parameters during mental fatigue are described in [11]. Most of the studies of EEG microstates deal with resting state microstates. Here an attempt is made to perform the analysis of microstates for EEG data acquired from a person while performing the NHPT, before and after a fatiguing condition that is induced using a wrist dumbbell exercise.

The rest of this paper is organised as follows. Section II explains the materials and methods used in the study. In Section III, the results of the study are explained and further discussion on the results is done in Section IV. Finally, Section V concludes the study.

II. Materials and Methods

A. Experiment Set up

The experiment setup includes an EEG signal acquisition device (g.USBamp), g.GAMMAcap, the haptic device Geo-

magic Touch which recreated the NHPT in a virtual environment and a physical rig for NHPT.

EEG signals from each participant are collected with the help of biosignal amplifier g.USBamp at a sampling rate of 1200Hz. EEG signals are recorded from electrodes FP1, FP2, F3, Fz, F4, FC3, FCz, FC4, C5, C3, C1, Cz, C2, C4, C6, and CP3 by means of g.GAMMAcap. Virtual and physical NHPT rig are localised in a way to provide an embedded reality task setup. A C++ code running on a Windows 10 (64-bit) machine using Visual Studio 2017 is used to configure the virtual reality environment and the Geomagic Touch. NHPT is performed using the stylus of the Touch device. The physical rig is kept in front of the participant and mapped onto a virtual rig on the LCD screen. There are nine pegs and a peg board on the screen. A peg is attached to the end of the stylus with the help of a rubber end cap. In each trial of NHPT, the participant has to pick the pegs on the screen one by one and insert them into one of the holes. The haptic feedback helps the participants to feel the virtual pegs. The time at which each peg is picked and released is recorded as peg status. At the beginning of the experiment, participants are allowed a practice run to get familiarised with the haptic device. Fig.1 shows a participant performing the experiment.

B. Experiment Protocol

5 healthy right-handed participants with no previous injuries to the upper limb or brain are recruited for the study. Table I has details about participants' physical characteristics. The total duration of the experiment, including setup time, for one participant, was 45-60 minutes. The ethics approval was obtained from the University of Hertfordshire under approval reference: ECS/PGR/UH/04035.

Two 4-minute-long EEG recordings are taken with eyes closed and eyes open at the beginning and end of the experiment. The participants are instructed to stay focused and try to minimise eye blinks, swallowing or any other motions that alter EEG recordings. Subsequently, they are asked to do two trials of NHPT followed by a fatiguing exercise for the forearm. Once the participants report fatigue, they are asked to do the next two trials of NHPT. There was no break given between end of the dumbbell exercise and the start of trial 3, however, 20 - 30 seconds elapsed between them during the experiment. The experiment flow is given in Fig.2.

TABLE I
PHYSICAL CHARACTERISTICS OF PARTICIPANTS

Subject	Gender	Age	BMI
1	Male	25	22
2	Female	36	21
3	Male	36	28
4	Male	34	36
5	Male	28	25

The fatigue exercise involves flexion and extension of the wrist using a dumbbell. Participants are asked to select one dumbbell from the set of weights provided and they are asked to perform 3 sets of 12, 10, and 8 repetitions with a 30 seconds rest in between the sets. All participants reported fatigue after the 3 sets.

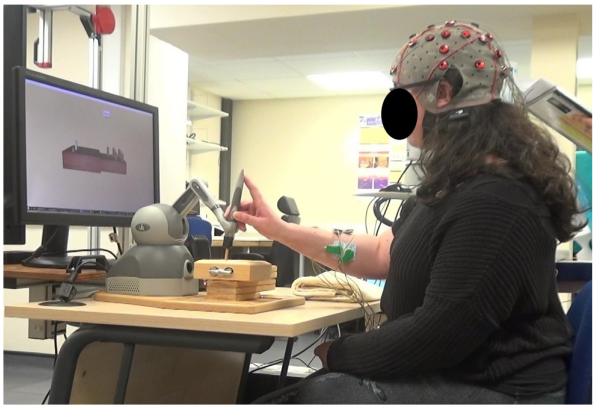

Fig. 1. A participant performing the NHPT experiment

A questionnaire is provided as part of the experiment in order to assess their fatigue status. Participants are asked to fill out parts of the questionnaire at the beginning of the experiment and requested to update their fatigue status before NHPT Trial1, after NHPT Trial2, before NHPT Trial3 and after NHPT Trial4.

C. Methodology

MATLAB R2019A is used to develop the EEG processing algorithms. The recorded EEG signals are segmented to extract data corresponding to each phase of the experiment and each NHPT trial. To remove high-frequency noise and low-frequency drift all signals are filtered in the frequency band 0.5-60 Hz using an FIR filter. Independent Component Analysis (ICA) is used for removing EEG artefacts [12].

Microstates are found for the resting state data at the beginning and the end. Also, microstates are found for pre-fatigue and post-fatigue NHPT trials. The EEG microstate analysis is performed with the help of the microstate EEGLAB toolbox in MATLAB 2019a [13]. The main part of the microstate analysis involved segmenting the EEG recordings into quasi-stable states using a clustering method. Modified K means clustering is used in this project to find the microstates. A two-step clustering is used to find microstate maps. The first clustering is performed on individual participants and in the next level, the clustering is done across the subjects [14]. Eye close data at the beginning and end are used for finding

Fig. 2. Experiment Flow and different phases

resting state microstates. Each of the recordings is segmented

into 20 sets of 2s data segments. The data is divided into 2s epochs. For the analysis of microstates, topographies at maximal potential field strength are considered. The strength of the scalp potential can be quantified using global field power (GFP), calculated as

$$GFP(t) = \sqrt{\frac{\sum_i^k \left(V_i(t) - V_{mean}(t)\right)^2}{k}} \quad (1)$$

where $V_i(t)$ is the voltage at electrode i at time t, $V_{mean}(t)$ is the mean voltage across all electrodes at time t and k is the number of electrodes [15].

The optimal signal to noise ratio and stable topography are obtained at the local maximum of GFP [16]. In the first step, the GFP of all aggregated data sets is generated. EEG maps that correspond to GFP peaks are submitted to modified K-means clustering for generating microstate prototypes. During the clustering, the polarity of the maps is ignored. Microstate prototypes are sorted by decreasing global explained variance.

Most of the literature predefined the number of microstates as four which previously has been reported as able to explain more than 70% of the total topographic variance [15]. In contrast, in this project, the number of microstates are selected based on the evaluation of prototype topographies and measures of fitness. The microstate clusters obtained at the individual level are then again clustered to obtain the global microstate maps [17]. Three microstates are observed for both the resting state and NHPT trials EEG. To find the microstate parameters, these global microstate maps are backfitted to the original EEG data [14]. After backfitting, microstate labels are smoothed temporally to remove small segments of unstable topography. For each microstate class, different microstate parameters are calculated.

The microstate parameters found here are the duration, occurrence, coverage, and global explained variance. The duration of a microstate is the average time for which a given microstate remains stable whenever it appears. The coverage of a microstate is the fraction of the total recording time when the given microstate is dominant. The occurrence is the average number of times per second a microstate is dominant [18].

III. Results

Initially, microstates are found for resting state data at the beginning and end of the experiment. Furthermore, microstates are found for the first peg transfer in trial 1 and trial 3. Both of these sets of microstates are shown in Fig.3.

A. Microstate analysis for resting state data

The participants are asked to keep their eyes closed for two minutes at the beginning and end of the experiment. Microstate analysis is performed on this EEG data to find any changes in microstate parameters while a person undergoes a fatiguing exercise. Three microstates A, B and C are found for the resting state data. The microstate parameters derived from the resting state data are shown in Table II. It can be seen that the occurrence of microstate A increases for all subjects except

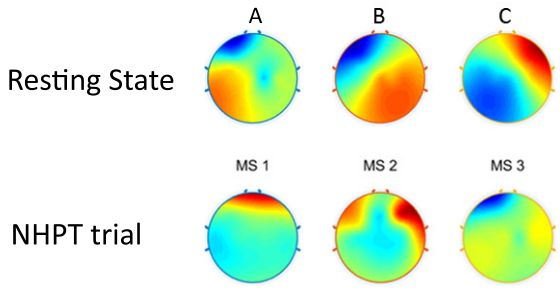

Fig. 3. Microstates during resting state and an NHPT trial.

subject 4. For microstates B and C, the occurrence increases for three subjects and decreases for two subjects. At the same time, the duration of microstate A increases for all subjects except subject 4. The duration of microstate B increases for three subjects and decreases for one subject. The duration of microstate C decreases for all subjects.

The Coverage of microstate A increases for all subjects except subject 4. The coverage of microstate B increases for three subjects and decreases for two subjects. The coverage of microstate C decreases for all the subjects. Changes in coverage for resting state microstates are shown in Fig.4. The global explained variance of microstate A increases for all subjects except subject 4. GEV of microstate B increases for three subjects and decreases for two subjects. GEV of microstate C decreases for four subjects and remains the same for one subject.

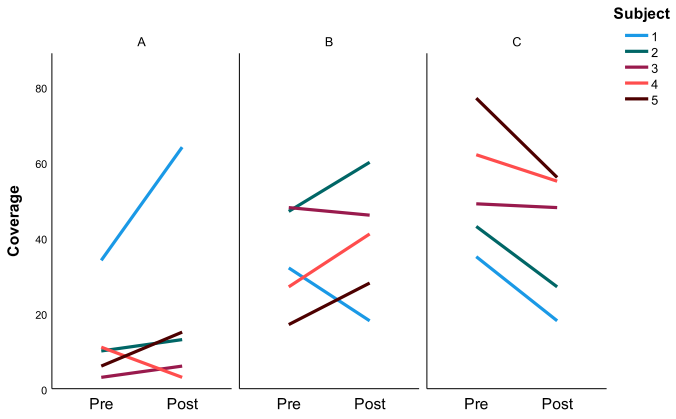

Fig. 4. Changes in coverage with fatigue for resting state microstates A, B and C.

B. Microstate analysis for NHPT trial data

The microstates are found when a person performs the first peg transfer in trial 1 and trial 3. Trial 1 is the first trial when

TABLE II
RESTING STATE MICROSTATE PARAMETERS.

Subject	Microstates	Occurrence			Duration(ms)			Coverage(%)			GEV		
		Pre	Post	Change	Pre	Post	Change	Pre	Post	Change	Pre	Post	Change
1	A	4.32	4.57	↑	78.34	150.32	↑	34	64	↑	0.17	0.36	↑
	B	4.12	3.10	↓	77.74	57.16	↓	32	18	↓	0.15	0.07	↓
	C	4.35	2.85	↓	80.18	61.47	↓	35	18	↓	0.19	0.08	↓
2	A	2.00	2.42	↑	49.68	54.79	↑	10	13	↑	0.03	0.03	
	B	4.72	4.45	↓	101.05	140.23	↑	47	60	↑	0.18	0.21	↑
	C	4.77	3.55	↓	92.85	76.75	↓	43	27	↓	0.17	0.07	↓
3	A	0.57	1.30	↑	40.00	44.26	↑	3	6	↑	0.00	0.01	↑
	B	4.20	4.60	↑	123.88	106.72	↓	48	46	↓	0.17	0.13	↓
	C	4.25	4.47	↑	119.89	119.71	↓	49	48	↓	0.18	0.15	↓
4	A	1.15	0.62	↓	72.49	30.90	↓	11	3	↓	0.02	0.01	↓
	B	2.37	3.57	↑	116.21	116.41	↑	27	41	↑	0.07	0.14	↑
	C	2.45	3.67	↑	402.22	165.44	↓	62	55	↓	0.25	0.25	
5	A	0.95	2.30	↑	47.18	64.40	↑	6	15	↑	0.01	0.03	↑
	B	2.75	3.75	↑	60.34	74.45	↑	17	28	↑	0.03	0.08	↑
	C	3.62	4.30	↑	233.95	145.44	↓	77	56	↓	0.32	0.26	↓

↑ and ↓ indicates increase and decrease of microstate parameters respectively

the participant is not fatigued yet. Trial 3 is the trial just after the fatiguing exercise and can therefore be called the post-fatigue trial. Three microstates are observed in the task EEG and named MS1, MS2 and MS3 in order to distinguish them from the resting state microstates. Just like for the resting state microstates here also the microstate parameters, occurrence, coverage, duration and GEV are calculated and tabulated. Table III shows the pre-fatigue and post-fatigue values of the microstate parameters.

For MS1 the occurrence increases with fatigue for two participants and decreases with fatigue for three participants. The duration of MS1 increases with fatigue for three subjects and decreases for the other two. The coverage of MS1 increases for all subjects except one. The global explained variance of MS1 increases with fatigue for all subjects.

For MS2 all the parameters increase with fatigue for three subjects and decrease with fatigue for two subjects. No MS3 is present for subject 2. In the other four subjects, duration, coverage and GEV decrease with fatigue for MS3. The changes in coverage for trial microstates are shown in Fig.5. The Occurrence of MS3 increases for one subject and decreases for three subjects.

C. Assessment of performance time during NHPT task for different trials

Table IV shows the time taken for each trial which is recorded with the help of Geomagic Touch API. A paired sample t-test is done between trial 1 and trial 3 and it is found that the time taken for post fatigue trial is not statistically different from the time taken for pre-fatigue trial(p-value 0.437). However, given the small number of samples, looking at the individual values for trial 1 versus trial 3, two participants (Subject 1 and Subject 2) show an increase in completion time while the remaining participants show an improvement in the peg-placement and task completion.

D. Questionnaire assessment of fatigue during experiment progression

The forearm fatigue status of each participant is recorded during the experiment. Participants are asked to update their fatigue status on a scale of 1 indicating not fatigued, to 10 indicating extremely fatigued, before trial 1, after trial 2, before trial 3 and after trial 4. The fatigue score of each participant is shown in table V. This table indicates that all participants report fatigue after the Dumbbell exercise, but the reduction of scores from before trial 3, to after trial 4, for participants 1, 3 and 5 could indicate an adjustment to the task complexity.

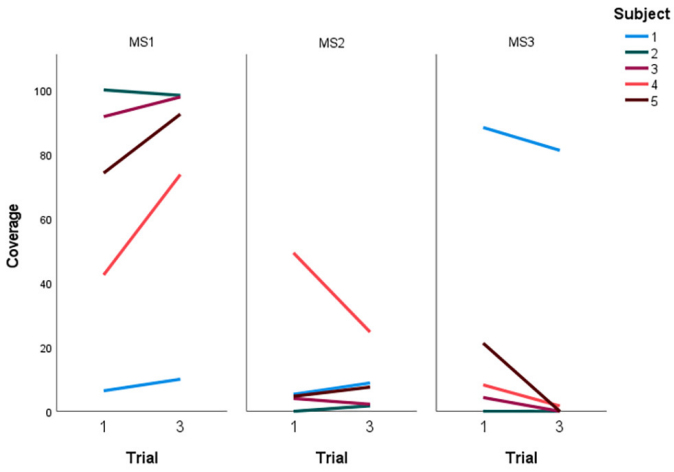

Fig. 5. Changes in coverage with fatigue for trial microstates MS1, MS2 and MS3.

IV. DISCUSSIONS

The present study investigates the changes in EEG microstates when performing an embedded reality NHPT, pre and post fatigue. To the best of our knowledge, this is the

TABLE III
TASK MICROSTATE PARAMETERS.

Subject	Microstates	Occurrence			Duration(ms)			Coverage(%)			GEV		
		Pre	Post	Change	Pre	Post	Change	Pre	Post	Change	Pre	Post	Change
1	MS1	0.81	1.52	↑	78.89	65.56	↓	6.40	10.00	↑	0.0023	0.02	↑
	MS2	1.08	1.28	↑	48.96	61.98	↑	5.30	8.82	↑	0.0035	0.01	↑
	MS3	2.16	3.31	↑	409.69	266.01	↓	88.30	81.19	↓	0.63	0.38	↓
2	MS1	0.29	0.67	↑	3.46*	1.76*	↓	100	98.29	↓	0.69	0.81	↑
	MS2	0	0.33	↑	0	25.69	↑	0	1.72	↑	0	0.0011	↑
	MS3	0	0		0	0		0	0		0	0	
3	MS1	1.86	1.00	↓	492.02	975.00	↑	91.68	97.79	↑	0.81	0.87	↑
	MS2	0.53	0.50	↓	75.42	44.17	↓	4.02	2.21	↓	0.0023	0.0015	↓
	MS3	1.06	0	↓	40.42	0	↓	4.30	0	↓	0.0054	0	↓
4	MS1	2.67	2.62	↓	154.72	399.78	↑	42.45	73.67	↑	0.30	0.61	↑
	MS2	2.67	2.24	↓	258.64	102.69	↓	49.31	24.67	↓	0.33	0.07	↓
	MS3	1.00	0.25	↓	69.21	33.13	↓	8.23	1.66	↓	0.02	0.0007	↓
5	MS1	3.92	1.31	↓	189.08	703.75	↑	74.13	92.45	↑	0.41	0.75	↑
	MS2	1.18	1.31	↑	39.72	57.50	↑	4.67	7.55	↑	0.01	0.01	↑
	MS3	3.92	0	↓	54.08	0	↓	21.20	0	↓	0.05	0	↓

↑ and ↓ indicates increase and decrease of microstate parameters respectively
*Duration of MS1 for subject 2 is in seconds

TABLE IV
TIME TAKEN FOR EACH TRIAL OF NHPT IN SECONDS

Subject	Trial 1	Trial 2	Trial 3	Trial 4
1	67	58	78	67
2	90	118	127	102
3	53	49	46	37
4	114	86	79	69
5	96	62	47	55
Mean (SD)	84 (21.59)	74.6 (27.85)	75.4 (32.99)	66 (23.81)

first study to identify microstates during the performance of a NHPT, and to reflect on changes to these microstates after a fatiguing exercise.

A. Resting state microstates

Several studies in the field of microstates found that microstate maps generally fall into four categories. However, in our study, we used the polarity invariant measures of fit global explained variance and cross validation to determine the optimum number of microstates and found three microstates for resting state data. Microstates B and C found in our study resembled resting state microstates B and A in the literature. It was interesting to investigate how microstate parameters like occurrence, coverage, duration and GEV changed when a person became fatigued physically and mentally. The dumbbell exercise in this experiment contributed to physical fatigue for the participants whereas performing NHPT using the haptic device Geomagic Touch provided a cognitive load for the participants. It was found that with fatigue all the parameters of microstate A increased for all subjects except one. The coverage of microstate C decreased for all subjects, which implies that fatigue made microstate C less dominant and increased the occurrence of other microstates. It could be seen that less coverage of microstate C was compensated by the increase in the occurrence of microstate B.

TABLE V
SELF-REPORTED FATIGUE STATUS

Subject	Before Trial1	After Trial2	Before Trial3	After Trial 4
1	1	2	8	7
2	1	1	8	8
3	1	1	8	6
4	1	4	9	9
5	1	2	8	7

B. NHPT trial microstates

Three microstates were observed in the EEG while performing NHPT trials. The microstate parameters were determined for transferring the first peg in pre-fatigue and post-fatigue trials (trial 1 and trial 3). MS3 was not present for one subject and, for all the other subjects, the coverage of microstate 3 decreased. This implies that new neural correlates were introduced with fatigue which reduced the coverage of microstate 3. While the coverage of MS3 decreased, the coverage of MS1 increased, which means that the fatigue caused changes in brain signals which created more MS1. A similar trend could also be seen in the GEV values. For MS1, GEV increased which was compensated by a decrease in GEV of MS3. The duration of MS1 was very high compared to the other microstates and it could be seen that its duration sometimes reached seconds. For subject 2 the duration of MS1 was in the order of seconds because only that particular microstate was present in the pre-fatigue trial, and in the post-fatigue trial, MS2 was present for a very short duration.

C. Performance time and fatigue status

Subject-score for fatigue for participants 1, 3 and 5 were reduced after trial 4, also there is an improvement in NHPT performance from trial 3 to trial 4. From Table V it can be seen that NHPT alone induces fatigue for subjects 1,4 and 5 after trial 2. But looking at the trial time there was a reduction in trial time for these subjects which indicates NHPT performance improvement. This could indicate that while

participants worked harder, and perceived to work harder, they actually improved their performance score as indicated by the reduction in peg placement time.

When comparing the time between trial 1 and trial 3, it can be seen that participants 1 and 2 took more time to complete NHPT when fatigued. Participants 3, 4 and 5 completed NHPT trial 3 in less time compared to trial 1, while all reported fatigue after the dumbbell exercise. These observations can indicate that physical fatigue alone is not impacting NHPT performance. This could be because these participants did not find the NHPT task challenging and haptic/visual assistance given to these tasks provided a good medium for reducing their completion time despite fatigue in their wrist. It could be also possible that the NHPT task involves a different neural assembly compared to the assemblies needed for the wrist exercise. Furthermore, it is possible that participants' fitness level could impact their recovery from fatigue. Participant 4 who had a higher BMI increased his fatigue level by doing NHPT alone compared to others. Comparing Table I and Table V it can be seen that participants with better BMI recovered soon from fatigue except for participant 2. No MS3 is present for participant 2 while NHPT trial time is more for each trial compared to others. Also, this participant struggled a lot to place the pegs in the hole during the experiment. This suggests that cognitive fatigue might also have an impact on MS3. Coverage of MS3 for all other participants decreased after fatiguing exercise which shows the impact of physical fatigue on microstates.

V. Conclusion

The present study investigated the changes in EEG microstates while a person performed a widely used manual dexterity test, the Nine Hole Peg Test, before and after fatigue conditions. The main goal of the study was to observe differences in resting state and task performance microstates and to observe the changes due to a physically fatiguing dumbbell exercise. We observed these differences, as highlighted by the topological maps, but also observed changes in the microstate parameters. With resting state microstates it was found that two of the microstates observed resembled the microstates already established in the literature [19]. It was also found that the coverage of some microstates decreased with fatigue for both resting state and trial data which was also backed up by a reduction in global explained variance. This suggests that assessing the microstate parameter coverage can help to identify physical fatigue. All participants reported fatigue on the forearm after the dumbbell exercise. We found that physical fatigue did not affect the NHPT performance as some participants reporting physical fatigue improved performance during the NHPT trials. However, alterations in microstate parameters were observed after the physical fatigue. We intend to further explore this by comparing the microstates during NHPT trials, with microstates observed during the dumbbell exercise. This can convey further information regarding the similarity or dissimilarity of the neural assemblies present during motor tasks performed in this experiment.

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