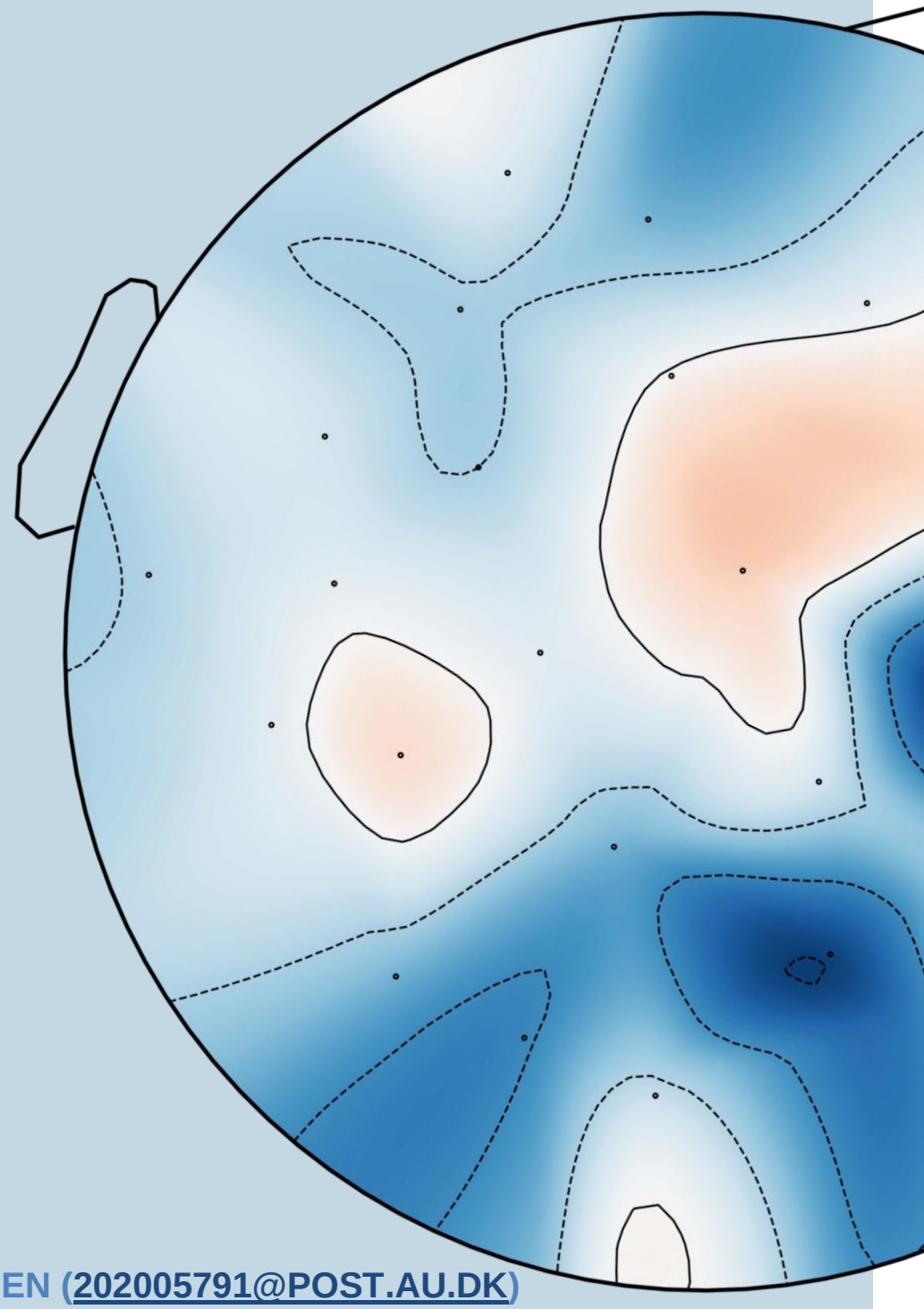
COGNITIVE AND MOTOR CONTROL WITH INTERFERING STIMULI

AN EEG AND MOUSE-TRACKING INVESTIGATION



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ABSTRACT

The human cognitive control systems are faced with a challenge when automatic processing of irrelevant information interferes with a task at hand. To resolve this interference, the ongoing response must be inhibited, and a new response suitable to the task must be planned and executed. A complex interaction between cognitive and motor control is needed to achieve this. This one subject preliminary study investigates the ERD and ERS of mu and Rolandic beta rhythms over the sensorimotor areas during an object discrimination task using EEG and mouse-tracking. The participant was instructed to identify an object, move the mouse cursor towards it, and click it. Two objects of high colour diagnosticity (i.e., objects highly associated with a typical colour) were presented, either in their typical colours (congruent), or in the typical colour of the other object (incongruent). A Stroop effect was found, revealing itself through longer reaction times for incongruent trials, but no effect was found on the maximum absolute deviation (MAD). To investigate if the congruency influences the neural synchrony a time-frequency analysis was conducted on epochs time locked to the response. Running a cluster-based permutation test on the time-frequency representation revealed a significant difference between the two conditions. Further analysis was conducted to investigate the signal over the sensorimotor areas (C3, FC1, FC3) through visual inspection of plots showing the power of mu and lower-beta bands over time. The results were discussed in terms of relevant literature.

Keywords: Mouse tracking, EEG, time-frequency analysis, ERD, ERS, Mu rhythms, Beta rhythms

Code: The code used for both conducting the experiment and carrying out the analysis can be found on GitHub (See https://github.com/laurabpaulsen/EEG_and_mouse_tracking)

This paper is the result of an exploratory analysis of data collected using mouse-tracking and EEG. It explores if there are any differences across conditions in terms of both mouse-tracking measures and time frequency of the EEG. Therefore, this paper should be considered an exploration of phenomena, that does not try to reach any conclusions but rather raise questions for further investigation, as well as testing this seemingly novel combination of methods.

COGNITIVE CONTROL AND THE MOTOR SYSTEM

Cognitive control is the ability to adapt our behaviour according to contexts, tasks, and internal goals. It is thought to consist of relatively separable processes such as inhibition and shifting (Miyake & Friedman, 2012). To investigate how cognitive control functions in the presence of task irrelevant stimuli, variations of the Stroop task are often used (Stroop, 1935; Tafuro et al., 2019). The cost of responding to the incongruent stimuli compared to the facilitation of congruent stimuli, is referred to as the Stroop effect. This effect has often been measured in terms of reaction times, but this type of output only shows the end of the cognitive process. Therefore, the current study uses mouse-tracking as it allows for examination of the dynamic correction of the cognitive process.

An important aspect of cognitive control, motor inhibition, is essential for regulating goal-directed behaviour in daily life. This is highly dependent on the motor system, which is crucial both for carrying out and stopping motor actions. The motor system consists of a set of central and peripheral structures that support motor functions, such as willful movement. One of the central structures is the motor cortex, which is associated with efferent neurons, carries information from the brain to the peripheral nervous system. Most of this information travels through the corticospinal tract in motor fibres where two thirds of the axons originate in the motor cortex. Before they reach the spinal cord, the signal decussates at the pyramidal decussation, at the junction of the medulla and the spinal cord. This means that the fibres that

originate in the left motor cortex innervate muscles on the right side of the body and vice versa (Bear et al., 2016, p. 486).

In terms of motor inhibition, it relies on reactive and proactive inhibition. Reactive inhibition, which is of most importance to this study, is a term often used within the stop signal task paradigm (SST). Here, it refers to the stopping of a response that has already been initiated triggered by a stop cue (Aron, 2011; Benedetti et al., 2020). As for neural systems involved in reactive inhibition, research using SST indicates that the stop signal is processed by frontal regions, such as the right inferior frontal gyrus (rIFG) and the presupplementary motor area (pre-SMA) (Neubert et al., 2010), which generates and sends a stop signal to the basal ganglia. A growing body of evidence supports basal ganglia, particularly subthalamic nucleus (STN), as a target of rIFC and pre-SMA to implement reactive inhibitory control (Meyer & Bucci, 2016). Finally, the premotor cortex and motor cortex are the last cortical sites involved before the signal travels down through the corticospinal tract. However, the SST has previously been discussed as being too simplistic to inform about reactive inhibition in more naturalistic settings.

ELECTROENCEPHALOGRAPHY (EEG)

It holds for both motor and cognitive functions, that they rely on neurons assembled in networks. Activation of such networks can be detected using EEG, as the signal measured arises from synchronous changes in the potential of the dendritic neuronal membranes of many neighbouring neurons. The cortical pyramidal cells are especially important to the EEG signal, as they produce extracellular dipoles. Based on the neurotransmitters released at the synapse, the synapse can be either excitatory or inhibitory. In the case of an excitatory postsynaptic potential (EPSP) the synapse is surrounded by negative charge, because of the inward cationic current. Intracellularly, the positive charge spreads within the dendrite. Along the dendrite, the efflux of cations evokes an extracellular positivity. This positivity is distant to the synapse, and

therefore a current starts to flow, towards the negative extracellular space near the synapse. When the postsynaptic potential is inhibitory the opposite is the case. If numerous neurons in the same areas contribute their small voltage, the signal can be large enough to be picked up by the electrodes positioned on the scalp (Bear et al., 2016). That is, if the neurons in the given region are oriented similarly, otherwise the dipoles might cancel out and it will not be possible to measure their activity (Luck, 2012). Additionally, the signal must travel through the brain, meninges, skull bone, and electrode gel to reach the electrode. EEG provides a good temporal resolution of milliseconds or less, but for reasons mentioned it does not provide good spatial resolution.

ERD AND ERS

One type of oscillations generated by the brain, which can be measured using EEG, is the mu rhythms (~7-12 Hz). The mu band is thought to reflect synchronised activity of the pyramidal neurons over the sensorimotor areas in the pre and postcentral gyri (Pfurtscheller et al., 1997). It is well known that planning and execution of movement can decrease or block the mu rhythms (Debnath et al., 2019; Neuper et al., 2006; Pfurtscheller et al., 1997). This phenomenon is an example of event related desynchronisation (ERD). On the other hand, event-related synchronisation (ERS) signifies an increase in the amplitude.

A classic example of ERD is the decrease in the amplitude of the alpha rhythms (~8-12 Hz) over the visual cortex after visual stimulation. There is a general agreement that an ERD can be understood as a correlate of an activated cortical area. It represents an activated state with enhanced information processing and excitability of cortical neurons in a specific system. On the other hand, large amplitudes of synchronised alpha (or mu rhythms) and lower beta band activity can be seen as an indication of a deactivated state where information processing and the excitability of the cortical neurons is reduced (Pfurtscheller, 2001). It should be noted however,

that different parts of the brain can be in different states, meaning that a high level of synchrony can be found over the motor cortex while sitting still, but at the same time the neurons in the visual cortex might be working in a more desynchronised manner to process visual stimuli. Furthermore, areas within the same modality can show different levels of synchronisation (Neuper & Pfurtscheller, 2001; Pfurtscheller & Lopes da Silva, 1999). For example, motor imagery of foot movement has been found to increase synchronisation over the hand area (Neuper et al., 2006). Moving from motor imagery to actual movement, unilateral movement of for example a finger, has been shown to result in ERD in both mu and beta bands over the contralateral sensorimotor area. This is followed by a beta rebound usually within a second of movement offset (Pfurtscheller, 2001).

To investigate ERD and ERS, time-frequency analyses are used. This allows better characterisation the oscillations in the EEG data compared to e.g., event related potentials (ERP) and Fourier-based power analysis (Morales & Bowers, 2022). By using time frequency analyses both non-phase-locked signals as well as the temporal information is taken into account, by separating phase information and power across multiple frequencies. These things are ignored by ERP and Fourier-based power analysis respectively. The former ignores non-phase-locked signals, while the latter ignores the temporal aspect of the signal.

This study aims to explore a novel combination of mouse-tracking and time frequency analysis of EEG data through an object discrimination task, where the incongruent task is thought to elicit reactive inhibition, or at the least require more cognitive control. To the knowledge of this author the combination of these methods has not been used before. Therefore, this paper rests on results from previous studies that do not fully coincide with it, such as the SST. It differs in the fact that the participant in the current study needs to reprogram the motor response, rather than just inhibit it. Furthermore, the stopping in SST relies on an external stop signal.

METHODS

PARTICIPANT

One healthy, right-handed, male volunteer participated in the study.

COGNITIVE TASK

The behavioural task is a near replicate of a mouse-tracking study (See Rasmussen & Markussen, n.d.). However, the experiment was coded using the PsychoPy package in python (as opposed to using OpenSesame), to allow for sending triggers with more specific timing to the EEG system. Furthermore, additional stimuli were added. The participant was exposed to an object discrimination task, in which two stimulus objects were presented. Before the presentation of these two stimuli, a cue presented for 1000 ms indicated which of the items the participant should click on. After a brief 200 ms pause, the two stimulus objects were presented.

The two stimulus objects differed according to three different trial types: (1) Congruent trials with stimuli coloured according to their typical colour, (2) neutral trials with stimuli displayed as achromatic line drawings, and (3) incongruent trials where the colours of the stimuli objects were switched (See Figure 1). Since colour has been found to influence object recognition, especially when it comes to high colour diagnostic objects (i.e., objects highly associated with a typical colour), this would be expected to elicit either a facilitatory or inhibitory effect (Tanaka & Presnell, 1999). Between each trial a 500 ms fixation cross was presented. The participant was given 9 practice trials, to ensure that the task was understood. As for the experimental trials, 51 stimuli pairs were displayed 3 times in a randomised order, resulting in 153 trials (51 trials per condition).

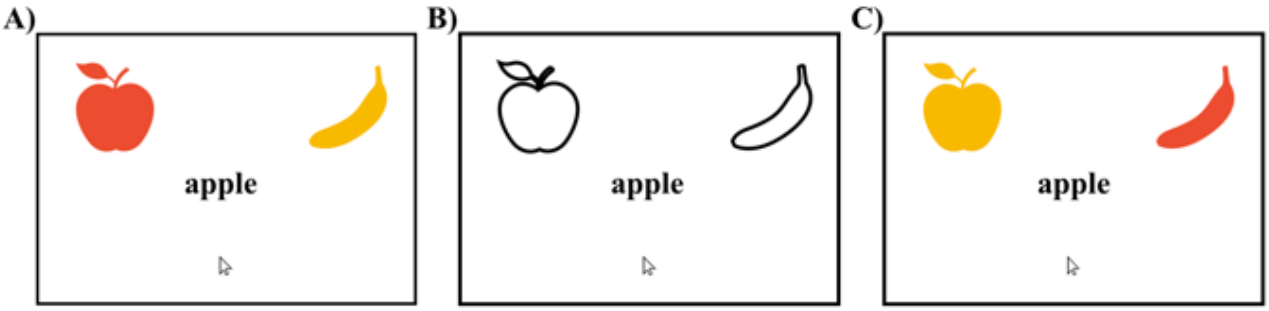

Figure 1: Examples of the three different conditions. A) illustrates a congruent trail, B) illustrates an incongruent trial and C) illustrates an incongruent trial.

Regarding the cognitive task, it is hypothesised that the typical colours in the congruent condition will facilitate object recognition, and therefore have a lower reaction time and maximum absolute deviation (MAD) than the incongruent condition, where the colours are expected to interfere with the task. In relation to response inhibition, it is expected that the incongruent condition might provoke an incorrect motor response that the participant will need to inhibit. This is hypothesised to result in a higher reaction time as well as MAD.

ANALYSIS

For the purpose of this study only incongruent and congruent trials were analysed, as the interest lies in how the incongruent/unexpected colours interfere, rather than the facilitatory and inhibitory effects respectively. This way emphasis is put on, how unexpected information might influence the mouse trajectories and EEG signal.

The mouse-tracking data was pre-processed using the mousetrap package in R (Wulff et al., 2021). Incorrect trials were filtered out for the analysis. The mouse trajectory was aligned onto a common start and end point. Linear regression was used to test the effects of condition on the RT, which was log-transformed to fulfil the assumption of the residuals being distributed as a Gaussian. The same analysis was conducted for MAD.

ELECTROPHYSICAL RECORDING

The EEG signal was recorded using a BrainAmp amplifier system, recording at 1000 Hz from 28 scalp sites arranged according to the 10-20 system. 2 EOG electrodes were placed respectively at the lateral canthus and above the centre of the left eye. All electrodes were referenced online to an electrode placed FCz. It is hypothesised that the EEG signal will differ across conditions. Furthermore, it is investigated whether the signal over the sensorimotor areas might also be influenced.

ANALYSIS

The offline processing of the EEG data was conducted using the MNE package in Python (Gramfort, 2013). EEG channels were referenced to the mean voltage of all channels (average reference) and two bad channels were removed (Fp1 and Fp2). Independent component analysis (ICA) was conducted to remove artefacts. To facilitate the identification of artefacts, a stronger high pass filter at 1 Hz was applied to a copy of the data set. The first two components found by the ICA were filtered out (See appendix 1a and 1b). ICA000 seems to capture the effects of eye-movement. In the time series plot, you can see evidence of saccades in the form of discontinuities surrounded by relative stationarity. This is reinforced by the scalp topography plot, as they indicate that the source origin is in or close to the eyes. The blinks can be seen very clearly in ICA001, especially in the time series which also corresponds to the movement detected by EOG-2. The ICA was applied to the raw unfiltered data, which was then high-pass filtered at 0.1 Hz and low-pass filtered at 40 Hz. Finally, epochs time-locked to the point at which the response was given were created and resampled to 250 Hz.

A time-frequency (TF) analysis was performed on these epochs using the time window from 300 ms to 500 ms as baseline. Only correct trials were included. The analysis was conducted on frequencies between 7 and 30 Hz in 1 Hz steps using Morlet wavelets. This was

done using the tfr_morlet function from the previously mentioned MNE package. A cluster-based permutation test was conducted on the time frequency representation, to determine if the signal differed across conditions. Furthermore, two plots were created, showing the mean power across conditions over three channels (C3, FC1, FC3) for two different frequency bands. This was done by averaging over the wanted frequencies for the specified channels.

RESULTS

BEHAVIOURAL DATA

It was found that trial type significantly predicted reaction time. The intercept ($\beta = -0.36$, $SE = 0.032, t = -11.45$, $p < 0.05$), shows that the mean reaction time in the congruent condition was 696.97 ms. The mean reaction time increased by 9.74% in the incongruent condition ($\beta = 0.09$, $SE = 0.045$, $t = 2.06$, $p < 0.05$). As for MAD no significant differences were found between conditions. The intercept ($\beta = -0.43$, $SE = 0.22, t = -1.94$, $p > 0.05$), shows that the mean MAD in the congruent condition was 0.65. The mean MAD is increased by 11.45% in the incongruent condition ($\beta = 0.11$, $SE = 0.30$, $t = 0.36$, $p > 0.05$). in MAD compared to the congruent condition ($\beta = 0.18$, $SE = 0.30$, $t = 0.30$, $p > 0.05$).

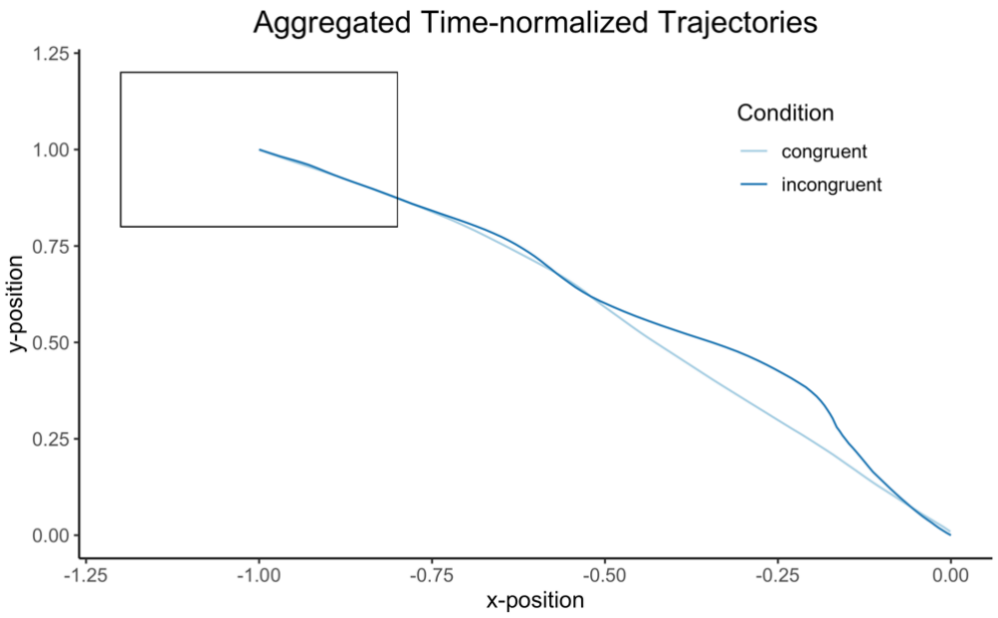

Figure 2: Aggregated time normalised trajectories for the congruent and incongruent condition.

EEG DATA

The cluster-based permutation test revealed a significant difference between the two conditions.

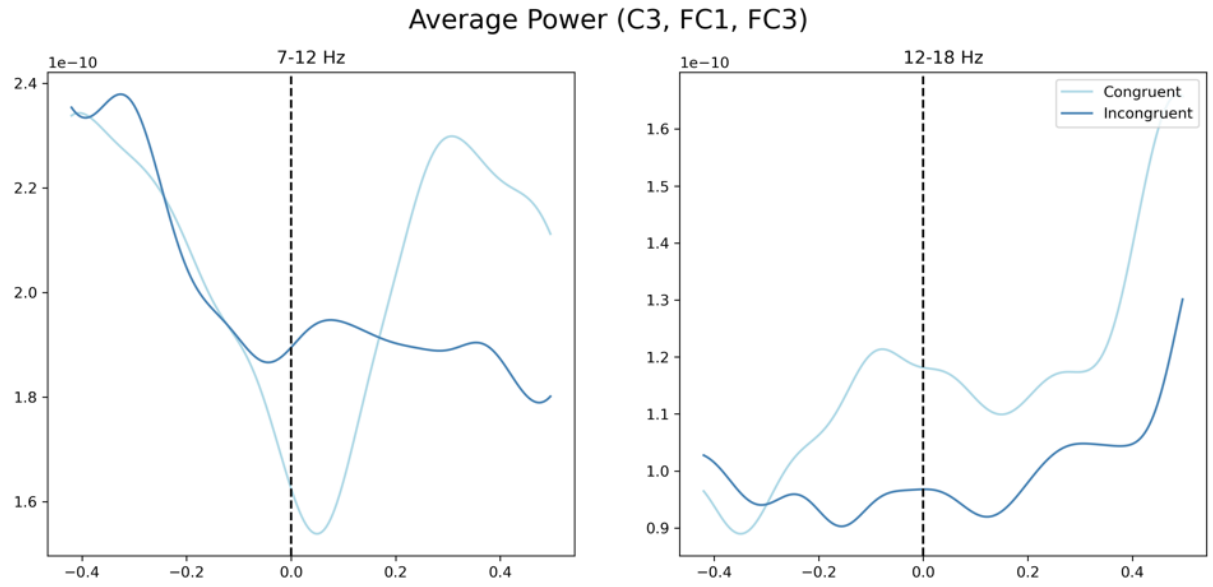

Figure 3: Averaged power for channels C3, FC1 and FC3 for mu (to the left) and lower beta (to the right) rhythms. The dotted line indicates the time at which the response was given.

DISCUSSION

The results from the analysis of mouse-tracking data support the hypothesis of reaction time varying across condition, which suggests that object discrimination was hindered by switching the colours of the stimuli. However, no significant difference was found for the MAD measure. This is also evident looking at the mean aggregated trajectories (See Figure 2), where the trajectories of the two conditions do not seem to differ much from each other, especially in comparison to results found by Rasmussen and Markussen (n.d.). This might be a result of several things. First, it might be that an effect is present, but is not strong enough to be found with the current number of observations. Besides, it was noted during data collection that the participant did not always begin moving the mouse shortly as the stimuli was presented (To remedy this other mouse-tracking studies include a reminder to begin moving the mouse if the participant has not done so within a certain time range). As a result, the ongoing cognitive

processing might not have been documented, as the participant might have carried out the object discrimination before moving the cursor towards the object in some trials.

The current study does not discriminate between trials in which the motor plan was reprogrammed under way, but rather analysis was done contrasting the conditions. Thus, it cannot be ruled out that reactive inhibition occurred only in the incongruent condition. Additionally, it is not certain that incongruent trials elicited reactive inhibition. A previous study looked at the velocity profiles extracted from mouse trajectories, to determine if a motor correction was made (Benedetti et al., 2020). This would allow for analysis of the signal in the motor cortex during reactive inhibition compared to trials where the correct motor response was initiated straightaway, rather than the of the oscillations during object discrimination with distracting stimuli. Though it was noted in the paper by Benedetti et al. (2020), that trials in which a correction was made had significantly longer reaction times. As mentioned, the reaction times in the current study were significantly longer in the incongruent condition, suggesting that there might be a larger proportion of trials with reactive interference in said condition.

With respect to the analysis of the EEG data, the cluster-based permutation test revealed significant differences between the two conditions. Additionally, of special interest were the mu and lower beta-band over the sensorimotor area contralateral to the hand controlling the mouse. As compared to the congruent condition, there is an indication of a prolonged ERD of the mu rhythms of the incongruent condition (See Figure 3). That is, it seems as if the power of alpha oscillations increases more quickly after the movement offset in the congruent condition, compared to the incongruent. Due to the design of the experiment, it is not possible to extend the time after the response, as the pause between trials was 500 ms (from response given until the word cue for the next trial is given). Therefore, the timing of the ERS in the incongruent trials cannot be determined. For the same reason, it is not possible to observe when the ERDs in the lower beta bands occur. However, since response times differ across trials, one could imagine

that desynchronisation would happen at different times relative to the time at which the response was given. This might result in a seemingly slow desynchronisation of the power, when averaged over trials. Time locking to the initiation of the movement could be an option for further investigation. What can be seen from the plot, however, is that the power of frequencies between 12-18 Hz seems to "rebound" quicker for congruent trials. Furthermore, the power increases a bit before giving the response, which is not the case for incongruent trials. According to Pfurscheller, the magnitude of the ERD reflects the degree of cortical activation and information processing. Under this assumption, there is an indication that in incongruent trials, information processing is ongoing for longer (signified by prolonged ERD in both frequency bands).

It should be noted however, that a previous study found that hand area mu rhythms were enhanced as during foot or tongue motor imagery (Pfurtscheller et al., 2006). This indicates focal ERD over the motor cortex rather than a widespread desynchronisation. This means that ERD in the hand area for example does not necessarily occur in isolation but can be accompanied by synchronisation in neighbouring cortical areas (Neuper & Pfurtscheller, 2001; Pfurtscheller & Lopes da Silva, 1999). This can be seen both within the same modality or between different modalities. Thus, the alpha desynchronisation seen averaged over the three channels (See Figure 3), does not correspond with the desynchronisation of the hand area, but is rather a measure of the activity over the sensorimotor area. Potentially, as the desynchronisation of the hand area occurs, a higher level of synchronisation might be induced in the foot area, influencing the power in the mu rhythms.

As described previously, response inhibition has often been investigated with the SST. In the current study, the stopping is not cued, but rather a result of realising that one is moving the mouse towards a wrong object in the incongruent trials where the colours successfully interfered with object discrimination. After this cessation of a motor response in progress, a new

response needs to be programmed, to move the cursor to the correct object. This adds some complexity to the task. Arguably, this is an advantage, as the SST has been criticised for being too simplistic, which raises the question if the findings generalise to more response inhibition in more real-world examples.

CONCLUSION

This study analysed mouse-tracking and EEG data from a single participant, who performed object discrimination between two stimuli presented in either their typical colour or the typical colour of the other object. A significant difference was found in the reaction time, but not for the MAD measure. It was discussed that the latter might be a result of the participant not moving the cursor before carrying out the object discrimination in some trials, and hereby the unfolding of the cognitive processing does not show itself in the mouse-tracking data. Using a cluster-based permutation test on the time-frequency representation, it was found that the signal differed across conditions. Looking further into the signal over the sensorimotor areas, there is an indication that there might be a discrepancy between the conditions when looking at the mu and lower beta oscillations.

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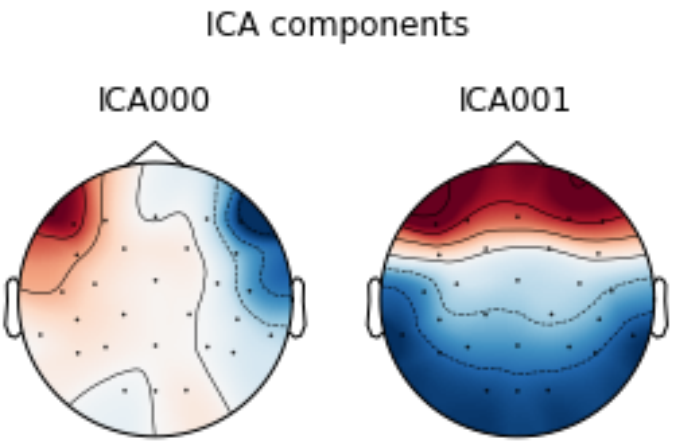
APPENDIX

APPENDIX 1

APPENDIX 1A - TOPO MAPS OF ICA COMPONENTS REMOVED



APPENDIX 1B - SOURCE PLOT OF ICA COMPONENTS REMOVED AND EOG'S