Effects of cycling speed on visual responses in the human sensory cortex

Ásta Guðrún Sighvatsdóttir

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HÁSKÓLI ÍSLANDS

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Supervisors: Barry Giesbrecht[2], Tom Bullock[2]

[1] Department of Medicine, University of Iceland, Reykjavík, Iceland [2] Department of Psychological and Brain Sciences, University of California, Santa Barbara, California, USA

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Abstract

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Ásta Guðrún Sighvatsdóttir[1], Barry Giesbrecht[2], Tom Bullock[2]

[1] University of Iceland, Reykjavík [2] University of California, Santa Barbara, California, USA

Introduction: The behavioral state of an animal influences ongoing brain activity and is evident when brain responses of anesthetic animals are compared to alert animals. In recent years, interest has increased on what effect physical activity might have on these responses, with research suggesting that visual processing becomes more sensitive during locomotion. Single cell recordings in the sensory cortex of rodents show an increase in firing rate of feature selective neurons as a function of exercise and similar responses are seen in EEG recordings of the human visual cortex. An increase in responses to feature selective visual stimuli in the human sensory cortex is shown to be greatest when participants are cycling at a low level of resistance, compared to conditions where they are resting or cycling at a high level of resistance, suggesting possible inverted-U effects of exercise workload on sensitivity in cortex. The goal of the present study was to extend previous findings and test whether manipulating pedaling speed on the bike can also modulate neural responses in visual cortex.

Methods: 11 adult volunteers (6 female, 5 male) took part in the study that was divided into two parts. Participants engaged in a visual orientation discrimination task in which they were presented with orientated gratings at one of nine different orientations and were required to detect a small rotation change. The gratings were flickered on and off at 15 Hz to generate a steady state response in cortex. The first part of the study involved determining a task difficulty level that the participant could perform at ~65% accuracy. In the second part, participants were positioned on a stationary exercise bike and completed the task at rest and during bouts of low (50 RPM) and high (70 RPM) speed pedaling. Each conditions lasted ~40 minutes. EEG, heart rate and pupil size were continuously recorded throughout each condition. An inverted encoding modeling (IEM) technique was applied to the EEG data to reconstruct estimated population-level neural response profiles.

Results: Preliminary analyses revealed a significant difference in response profiles between rest vs. low cadence, [$t(10) = 2.28$, $p=.045$]. Furthermore, there was a significant difference in rest vs. high cadence in activity at 15 Hz, [$t(10) = 2.32$, $p=.04$].

Discussion: The results seem to be trending in the same direction as the previous work, such that low-intensity exercise appeared to increase feature selective attention responses. The sample size of this study is currently rather low, but with more participants (n=18), we predict statistically significant differences in response profiles between rest and low-speed exercise conditions.

Ágrip

Áhrif breyting á hjólatakti við hreyfingu af lítilli ákefð á sértæka athygli í sjónberki manna

Ásta Guðrún Sighvatsdóttir[1], Barry Giesbrecht[2], Tom Bullock[2]

[1] University of Iceland, Reykjavík [2] University of California, Santa Barbara, California, USA

Inngangur: Meðvitundarástand lífveru hefur áhrif á úrvinnslu taugaboða í heilanum og eru greinileg þegar viðbrögð svæfðra dýra eru borin saman við vakandi dýr. Á síðustu árum hefur áhugi kviknað á mögulegum áhrifum hreyfingar á heilann þar sem stakfrumumælingar í skynberki nagdýra sýna aukningu á taugaboðum í tengslum við sjónræna örvun sem svar við hreyfingu. Svipað svar hefur mælst í heilum manna þegar heilarafrit er notað, en aukning sést sérstaklega í tengslum við hreyfingu af lítilli ákefð (low-intensity). Markmið þessarar rannsóknar var að skoða áhrif hreyfingar á úrvinnslu taugaboða og þá sérstaklega skoða möguleg áhrif breytingar á hjólatakti (cadence) við hreyfingu af lítill ákefð á eiginleika sértækrar athygli (feature-selective attention).

Efni og aðferðir: Grunnrannsókn með 11 einstaklingum (6 kvk, 5 kk) skipt í 2 hluta. Í fyrri hluta (1.5klst) lærðu þátttakendur á verkefni sem kannaði ákveðna eiginleika sértækrar athygli, og þröskuldsgildi (65% rétt svarhlutfall) hvers og eins í verkefninu mælt. Í seinni hluta (4.5klst) var heilarafrit mælt á meðan þátttakendur framkvæmdu athyglismælingu í þrenns konar ástandi; viðmið og tvenns konar hreyfing af lítilli ákefð, í tilviljunarkenndri röð. Í viðmiðunarástandi stöppuðu þáttakendur fótum við 50 rpm takt og í hreyfingu var hjólað í 50 rpm og 70 rpm takti. Þáttakendur sátu á kyrrstæðu hjóli, með olnboga á handfangi til að minnka aðra hreyfingu og hendur fríar til að svara athyglismælingunni með mús fastri við hjólið. Athyglismælingin gekk út á að svara hvort blikkandi (15 Hz) hringur með svörtum og hvítum línum, sem birtist á skjánum í 2 sek, snérist réttsælis eða rangsælis. Afstaða línanna birtist tilviljanakennt í einni af 9 afstöðum á skjánum og var erfiðleikastil mælingarinnar við 65% þröskuld einstaklingsins. Mælingin á að meta getu manna til að nema mismunandi afstöðu og breytingu á henni og þar með einn eiginleika sértækrar athygli. Í hverju ástandi fyrir sig framkvæmdi einstaklingurinn verkefnið 360 sinnum (fullgildar tilraunir). Hjartsláttartíðni og hjólataktur voru mæld í Trainer Road forriti. MATLAB og EEGLAB forrit voru notuð í gagnavinnslu og IEM aðferð var notuð til að skoða mynstur taugaboða í tengslum við sjónrænu örvunina.

Niðurstöður: ANOVA fervikagreining á gögnum heilarafritsins sýna ekki marktækan mun á mynstrum taugaboðanna þegar allar 3 meðferðirnar eru bornar saman. Hinsvegar sýnir parað t-próf marktækar niðurstöður [$t(10) = 2.28$, $p=0.045$] á aukningu taugaboða við hreyfingu, þegar viðmið og hjólataktur við 50 rpm eru borin saman. Engan munur mælist á viðmiði og hjólatakt við 70 rpm eða þegar bæði hreyfingarinngrip eru borin saman.

Ályktanir: Marktækni á milli hvíldar og hreyfingar við 50 rpm hjóltakt benda í sömu átt og fyrri niðurstöður, að hreyfing af lítilli ákefð hafi áhrif á taugaboð sértækrar athygli. Hins vegar var þýðið of lítið og má áætla frá fyrri rannsóknum á mönnum af svipuðu sniði að með stærra þýði (n=18) muni niðurstöður verða marktækar. Hversu mikil og hver nákvæmlega áhrifin hreyfingar eru á sjónræna úrvinnslu heilans eru enn óljós og spennandi að sjá hvað frekari gagnasöfnun hefur í för með sér.

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1 Introduction

1.1 The visual cortex

The visual cortex is one of the most researched areas of the brain, with important studies dating back to the 1960's giving insight into organization of the brain cells in relation to function and visual processing (1). The primary visual cortex, often called V1 or striate cortex, is the main visual processing area of the brain found in all mammals. It is located in the occipital lobe of the brain, receiving visual information relayed through the lateral geniculate nucleus (LGN) from the retina of the eye. It is often divided into 6 layers with different functional groups of neurons and connections (2). All studied mammals have some form of columnar organization in the V1, where groups of neurons with similar response characteristics come together in a column mapping out the visual field. Even though there is variability in the response characteristics of neurons within the groups, these certain groups of neurons react in a predictable way to different features of visual stimuli, such as orientation, color, texture and spatial frequency. Feature-selective neuron responses, especially when it comes to different orientation of bars of light or contrast of lines, are consistently seen across different mammalian species (2). Neurons react selectively to different stimuli, such as size, position, and orientation, as shown in single cell recordings in the striate cortex of cats, where the retinas of the eyes were stimulated by spots of light. How the neurons react is based on the organization of excitatory and inhibitory regions in the receptive field, with specific types of neurons firing more at one certain stimuli and other types of cell reacting more to another type of stimuli (1). Research in macaque and spider monkeys showed similar results as in the cat, but with a greater sensitivity to change in orientation of the stimuli and smaller receptive fields, as well as signs of ocular dominance. (3). This ability to detect a change in orientation is also seen in mouse visual cortex(4).

Since it is not feasible to record a single cell in the human brain (except for clinical purposes) other methods need to be used. Feature selective responses, such as to different orientations, can be estimated in human visual cortex, but at the population level, using data obtained from functional magnetic resonance imaging (fMRI) (5) as well as an electroencephalography (EEG) (6).

1.2 Exercise and feature-selectivity

It is evident that visual stimulation is not the only factor when it comes to responses in the sensory cortex and that the behavioral state of an animal has an important impact on global brain activity. This is evident in research looking at visual processing in anesthetized versus awake animals, where anesthesia affects processing in V1 by altering the duration of sensory evoked responses and suppressing other responses (7) (8).

That raises the question of whether physical exercise (another form of behavioral state change) might affect brain activity.

1.2.1 Non-human animals

Single cell research in flies, specifically the vertical-system visual neurons in the Drosophila, found that the neurons become much more responsive when flying compared to rest. During flight, the membrane potential decreased, indicating that the neurons become more sensitive, resulting in increased synaptic responses (9). There also seems to be a correlation between walking speed and amplified responses in neurons of the horizontal system in the Drosophila, indicating that the type and amount of exercise plays an important role in the magnitude and overall response of locomotion in V1 (10). Similar response to exercise is seen in V1 neurons in the mouse visual cortex when data collected while running is compared to standing still. A significant increase in feature-selective responses is measured as a function of the exercise without changing the selectivity of the neurons (11). The response in mice is also seen as a change in spatial integration, where suppression of the surroundings becomes smaller, allowing V1 neurons to retrieve stimuli from a larger area (12).

In mouse visual cortex, a link between a specific type of GABAergic cortical neuron, the vasoactive intestinal peptide (VIP)-positive neuron, and the gain in visual responses as a function of locomotion. Where optogentetic activation of the VIP neurons produced a similar gain in visual response as induced by exercise and damage to the VIP neurons decreased the response to exercise significantly (13).

1.2.2 Humans

The extent to which these results are transferrable to reaction-to-exercise in the human sensory cortex is still a very new and interesting topic of research. Nonspecific to the region of the human cortex, an increased activation in theta, alpha and beta frequency has been measured as a function of moderate exercise (14).

Overall there seems to be at least a small positive effect of exercise on cognitive performance, but research suggest it varies after style and duration of exercise as well as type of assessment used to measure cognitive activity (15). Acute bouts of exercise seem to have an impact on parts of brain activity such as performance at a cognitive task and related brain activity. High-intensity bouts of exercise seem to increase target detection speed in a behavioral task, when compared to rest and low-intensity, while also affecting other stages of visual processing. Bouts of low-intensity exercise show an increase in amplitude of sensory evoked responses at the parietal-occipital electrode when compared to rest and high-intensity bouts. At both high- and low-intensity bouts of exercise the event related potential components evoked by the visual stimuli show a peak earlier when compared to rest, with low-intensity connected to the early stage processing (P1) in and both high- and low-intensity in relation to the later stage of processing (P3a) (16). However, some research has shown a slight decrease in performance when meta-analytic research techniques are used, but this also appears linked to the type of exercise and to instances in which the cognitive assessment take place during the bout of exercise (13).

Indications are that an individual's aerobic capacity plays a part in performance on a visual search task when completed while exercising on a bike, with better aerobic capacity translating into better performance on the task (17).

1.3 Knowledge gap

The course of this effect on brain activity in animals and humans as a result locomotion is still unclear, as to how much and what mechanism lies behind. Further investigation into how the brain processes visual stimuli while active is an important topic and the mechanisms underlying enhanced performance during low-intensity exercise are not currently understood.

1.4 Research goal

The purpose of the study was to further investigate the effect of physical activity on feature-selective responses in the human visual cortex, with an emphasis on different cycling speeds at 50 rpm and 70 rpm cadence.

2 Materials and methods

2.1 Participants

11 adult volunteers from the University of California, Santa Barbara, community took part in the study in exchange for either pay of $20 per hour or course credit. The sample size was determined by previous studies looking at the effect of exercise on feature selective attention (18), studies that have used an IEM approach to EEG data (6, 19) and research focusing on the effect of exercise on cortical activity (14, 20, 21). Demographic data is reported in Table 1. All participants reported having perfect vision, except two that had contact lenses that did not to interfere with necessary experiment procedures, such as eye tracking. Participants completed a Physical Activity Readiness Questionnaire, by the National Academy of Sports, to determine if they were fit to partake in a study that involved aerobic activity. No one was excluded on that basis. Informed consent was obtained before each study session after the experiment had been explained thoroughly and they had been informed of their rights as human subjects. The University of California, Santa Barbara, Human Subjects Committee and the U.S. Army Human Research Protection Office approved all procedures.

Table 1: Means for demographic and cardiovascular data

Measure	***Mean Participant Information***
n	11 (6 female)
Age (years)	23.27
Resting heart rate (BPM)	72.43

2.2 Bike Setup

For the exercise part of the study a stationary bike, CycleOps 400 Pro Indoor Cycle (Saris Cycling Group, Madison, WI), was used with T2PLUs Profile Design Aero Bars (Profile Design, Long Beach, CA) attached to the handlebars. The handlebars served two purposes, first to minimize upper body movement of the participant while exercising for the sake of eye tracking and to decrease noise in EEG recording. It also freed the hands so participants could answer the visual discrimination task by pressing a mouse, Logitech Trackball Mouse (Logitech, Newark, CA), that was fixed at the end of the bars. During the exercise conditions, the feet were placed on pedals with a pedal strap so the foot would be held in place, making the biking easier. In the resting condition, the pedals were detached from the bike and replaced by Styrofoam-reinforced cardboard boxes for foot-tapping. The standard CycleOps bike seat was replaced with a new seat designed to limit discomfort from sitting on the bike for an extended period of time. Participants also received a pair of disposable bike shorts for the same purpose.

Trainer road software (Trainer Road, Reno, Nv) was used to adjust the resistance of the bike while pedaling, 50 Watts in both exercise conditions, and measured the cycling speed or cadence. A CycleOps wireless heart rate monitor measured the participants' heart rate and stored data in Trainer road. The

equipment setup is based on setup in previous studies looking at the same (22) or similar topics of research (16, 17, 23). Equipment setup is shown in Figure 1(18).

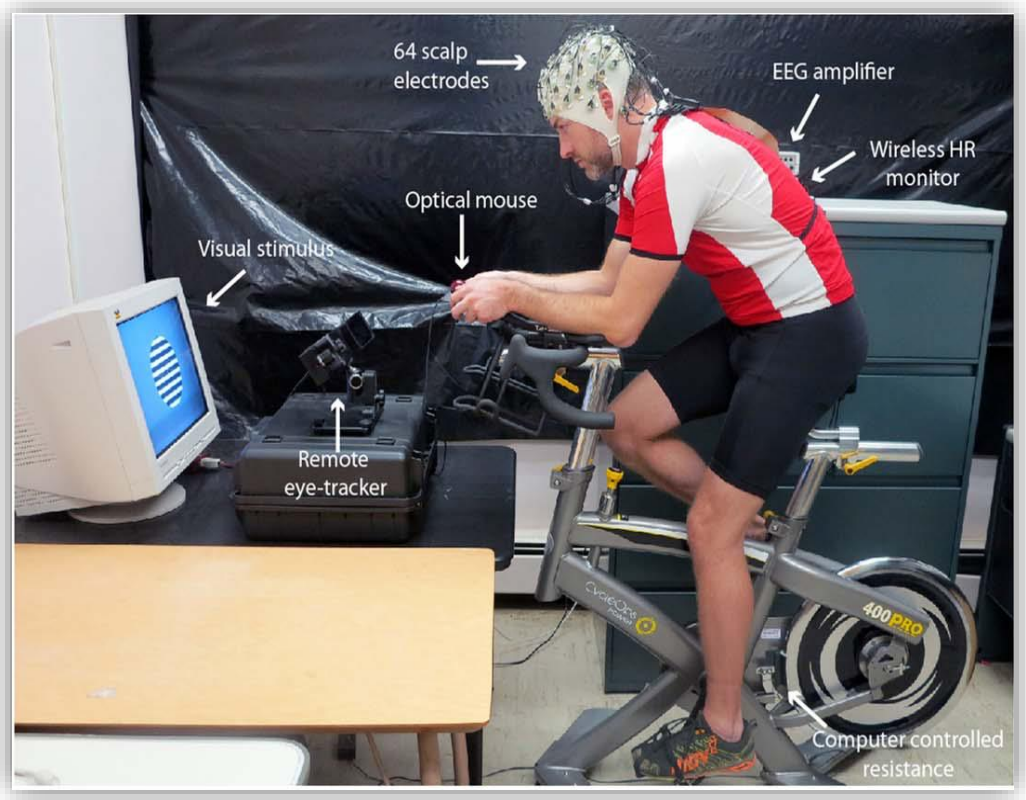

Figure 1: Equipment set up

2.3 Visual Stimuli

In order to measure feature selective attention a visual discrimination task (Figure 2) (18) that consisted of circular, square wave grating visual stimuli with a central fixation point was performed. The stimuli were presented on a 19-inch, ViewSonic E90f CRT, monitor positioned at a distance of approximately 100 cm. The Psychophysics Toolbox for MATLAB (Brainard, 1997) was used to run custom scripts with the stimuli and commands for presentation on the screen. An eye tracker (Eyelink 1000 Plus, SR Research, Ltd., Mississauga, Ontario, Canada) was used to track eye movements. The eye-tracking was gaze contingent, meaning that if the participant looked away from the centered fixation because of an eye blink or looking away, the trial was broken and the task started again. This enabled us to determine the number of quality trials and keep them the same amount for each condition across all participants (8).

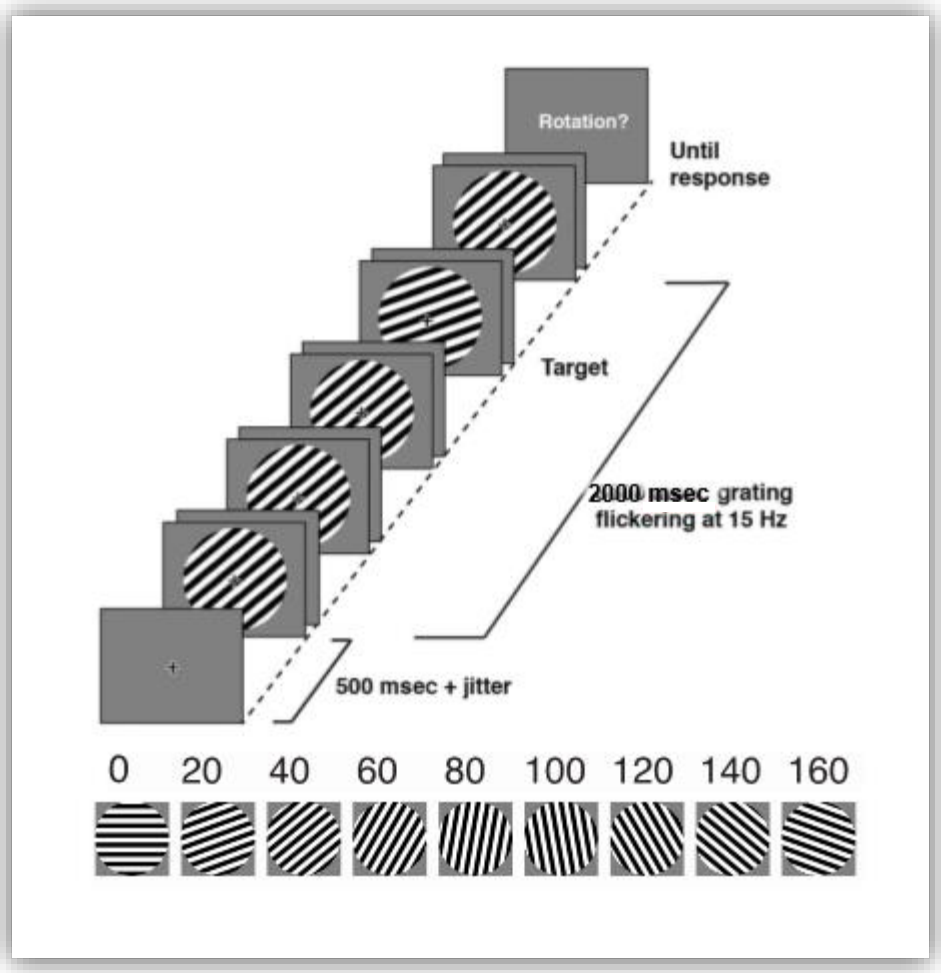

Figure 2: Example of the orientation discrimination task. Participants focus on the cross in the center and try to detect the target or shift in orientation. Shown are the nine different orientations at which the stimuli were presented.

2.4 EEG recording and preprocessing

An EEG system with 64 electrodes was used and three different sizes of EEG caps (56, 58, 60 Caucasian). For offline processing of the EEG, data scripts in MATLAB (version R2017a, Massachusetts, The MathWorks, Inc., Natick, MA) were used along with EEGLAB toolbox (Delorme & Makeig, 2004). First the data was high-pass filtered at 4 Hz and low-pass filtered at 20 Hz to remove possible noise in the data from frequency activity caused by sweating and muscle movement respectively. Next the data was epoched between 0-2 seconds and all broken trials, where the central fixation was broken by a blink or eye movement, were removed. No artifact rejection routine was done, but channels measuring head, eye and leg movements were removed from the dataset. Early onset trials, making up 20% of the trials, where the target or orientation shift appeared in the earlier part of the 2 seconds instead of at the end were excluded from the data. A Fast Fourier transform function (fft.m) in MATLAB was used in the last part of preprocessing the EEG data to convert the 2 seconds of data to a single-sided Fourier spectrum.

2.5 Procedure

The experiment was performed in two sessions. The first session served three goals; explain the experiment procedures to the participant, make sure the equipment worked, and measure individuals' performance threshold. After the participant was familiarized with the study and their rights as a human subject, an informed consent in writing was received. Next the participant filled out a Physical Readiness Questionnaire (National Academy of Sports Medicine), to determine whether they were suitable to partake in a study with aerobic activity. An important step was to see if the eye tracker, used in the visual discrimination task, worked with the individual's eyes. At last the individualized performance threshold for the orientation discrimination task, performed in the second session, was measured with the Method of Constant Stimuli. The method uses a spectrum of circular wave grating flickering stimuli presented at 9 different orientations, same as in the main visual task, but with 6 different difficulty levels. The difficulty level was manipulated by changing the degree of the orientation shift, or rotation, where more degrees meant a bigger shift and therefore easier detection. The participant was familiarized with the visual discrimination task by completing at least 10 trials at each level, starting with the easiest or biggest change in orientation and then the other 5 difficulty levels, ending with the hardest or an impossible to detect shift in orientation. By doing this, information of the individual's performance ability on the task was gathered as well as training the participant at the task.

The task was performed sitting still on the stationary bike with the pedals detached and boxes beneath the feet for toe-tapping. The toe-tapping served the purpose of making the resting condition a dual task, like the biking conditions (which involved concurrent performance of the orientation discrimination task and matching pedal speed to the beat of a metronome), without making the participant partake in aerobic activity. After seeing that the participant understood the task and could tap their toes to a beat of 50 rpm, a scale of difficulties for the task was set for the method of constant stimuli. In all cases but one the scale of (0.5, 0.7, 0.9, 1.1, 1.5, 2,4) was used, where the number represents the degrees of the orientation shift, 0.5 being the smallest shift, or hardest, and 4 being a very detectable shift, or the easiest. The method is designed to capture the spectrum of difficulty levels from the hardest being undetectable, or with the odds of a correct response being equivalent to chance (50%), to the biggest shift being detectable almost every time, or around perfect (100%) performance. Next, participants sat on the stationary bike, tapping the toes to the sound of a 50 rpm beat coming from a metronome and performed 420 trials of the visual discrimination task at six different difficulty levels appearing in random order.

One trial consisted of the circular grating stimuli flashing on an off at 15 Hz for 2 seconds with a shift in orientation sometime at the end of the trial. After the trial a blank screen appeared with the text "Orientation?" and the participant replied with the right mouse button and reported if they detected a clockwise rotation or the left mouse if the rotation was anticlockwise. Participants responded even if they did not detect a shift, as was expected for the hardest difficulty level. Every 10% of completed trials, specifically trials that were not broken by a change in fixation or head movement, there was a 20 second mandatory break. The break was meant to ensure the participant did not rush though the task and got

a chance to rest the eyes, ensuring fewer blinks because of dry eyes and greater comfort over all. The first session took around one and a half hours, with approximately 40 minutes for the Method of Constant Stimuli procedure.

In the second session, called the main session, 12 out of the 17 participants in the first session came in for further evaluation. Out of the 5 participants that were excluded, 2 were excluded because of inadequate eye-tracking, other 2 because task performance at the easiest orientation shift was still around chance and then 1 participant decided not to continue the experiment after finishing the first session. For the remaining 12 participants the second half of the experiment was explained and informed consent was obtained again in writing. A wireless HR monitor was attached right below the sternum and disposable padded underwear was gifted to the participant if wanted, to make time on the bike more bearable. Next an appropriately sized EEG cap for the individual's head circumference, measured during the first session, was put on the participant. The cap was positioned by measuring anatomical marks such as the distance from the nasion on the forehead and inion on the back of the head. The first electrode in the middle at the front of the EEG cap, for the ground electrode, was placed at 10% distance of the length from the nasion to inion. The cap had all the electrodes already attached, making sure that each one was put in the right place according to the 10-20 electrode system with 64 electrodes. The electrodes were connected to the EEG amplifier and an impedance check was started on the computer attached. All the electrodes were filled with gel, starting with the ground electrode in the frontal area. When filling the electrodes with an appropriate amount of gel the syringe is also used to move the hair out of the way for a better signal. After all the electrodes had reached a good signal of connectivity, the participant got on the stationary bike.

Three conditions were conducted in a random order. In the rest condition, the participant tapped their toes to a beat of 50 rpm, similar to the first session. In the biking conditions they pedaled at 50 rpm in one condition and 70 rpm in the other biking condition. At start of every condition, 72 trials were completed to get them familiarized with the task again while tapping the toes or biking, varying on the condition. The difficulty of the task was set at a 65% threshold, calculated from the method of constant stimuli, and remained the same throughout all the conditions, different from the first session where it changed in difficulty threshold. After the training trials, all equipment was checked, including the eye-tracker, and then the main experiment started with a five-minute baseline period.

The baseline period participant fixated on a cross in the middle of a blank gray screen for 30 seconds and then closed their eyes for 30 seconds. This round of opening and closing eyes was completed five times, for 5 minutes in total, while toe tapping or biking at the cadence appropriate for the condition. In the baseline period clean EEG data was recorded without any visual stimuli responses and could be important in processing of the data. Next there was a 3 minute warm up period, with no required fixation on the screen, but biking or toe tapping. During this time, participants got an opportunity to get in a good rhythm on the bike and the experimenter had a chance to coach if the cadence was off. Between the warm up and the next portion of testing, a little break was offered to make sure that the participant was comfortable.

The main experiment consisted of 4 blocks of 90 trials, 360 unbroken trials in total, of the orientations discrimination task completed at an individual's 65% threshold. A 10 second forced break was given at every 18 unbroken trials to rest the eyes and prevent rushing through the task. An arbitrary measurement of perceived exertion was used to monitor the participants comfort level, where a scale with several statements of perceived level of exertion was shown on a gray blank screen and the participant asked to answer. This was asked after the warm up, after block 2 and at the end. At the end of each condition, an impedance check was completed to check electrode connectivity and a baseline recording, where the subject stood still for a couple of seconds while the computer recorded the brain activity after the condition for a brief moment.

A 10 to 15 minute break was given in between each condition to rest the body and prepare for the next condition. HR and cadence were monitored throughout the whole experiment, with an accelerometer attached to the foot of the participant to measure for the cadence of the pedaling and toe tapping. Accelerometers were also put on the head to monitor head movement as that can cause noise in the EEG data.

2.6 Spectra Classification Analysis

A linear discriminant classifier was used to see if the visual stimuli evoked a response and to what extent the response carried information about orientation. The classifier had been trained to estimate the power and phase angle with real and imaginary components of the Fourier coefficients at the stimulation frequency, 15 Hz. A leave-one-out cross-validation was used to test the classifier where performance was evaluated by looking at the proportions of correct classifications of all the classifications and comparing it to chance (1/9 = 0.111).

2.7 Inverted Encoding Model

An inverted encoding model (IEM) used the spatial distribution of stimulus-evoked activity across the scalp to look at orientation-selective tuning profiles specific to the sensory evoked responses. The first part of the model is to look at how well the basis set, a linear combination of priori canonical responses, represents the structure of the measured data. The second part is designed to see how much information about the stimulus features the response pattern actually contains. Therefore, seeing if it can accurately portray the stimulus reconstruction and quantifying the overall shape of the reconstruction. The method was initially used in fMRI studies but has recently been used in studies measuring the effect of exercise on feature-selective tuning profiles with an EEG (18).

IEM has a training portion, using all trials but one, and a testing portion where the remaining trial is used. For each individual and condition, number of electrodes in the data set was represented by m, number of trials in the training set represented by n_1 (287 trials) and number of trials in the testing set with n_2 (1 trial). Hypothetical orientation channels (nine equally spaced orientations) represented by j

were raised to the seventh power give an approximate of orientation bandwidth of orientation selective cells in the primate V1 for the basis set (18). Data was separated into independent training and testing sets, with each trial being a training and testing trial at least once. For each iteration B_1 (m x n_1) represented the training set, B_2 (m x n_2) the test set and C_1 (j x n_1) the basis set. To estimate the weight matrix W (m x j), the basis set and a general linear model was used

$$B_1 = WC_1$$

then an estimate of ordinary least square of W could be computed as

$$W = B_1C_1^T(C_1C_1T)^{-1}$$

and channel response (C_2) estimated by using the estimated weight matrix (W) and the test set (B_2) with

$$C_2 = (W^TW)^{-1}W^TB_2$$

After the channel response (C_2) was calculated for each orientation, the response at each trial was shifted to a common stimulus-centered frame and the centered response was averaged. After that a point at 0 degrees on the x axis was referred to the orientation of the stimulus that evoked the response profile. The last step was to take the square of the absolute value of the stimulus-centered response and get a measure of power (μV^2) for the tuning profile of the feature selective response.

2.8 Hypothesis testing

An important part of data processing is checking the statistical significance of the data. Here an ANOVA was used to determine if there was a difference somewhere between the conditions and t-tests to determine which pairs of different conditions were contributing to this effect. T-tests were completed even in the case of non-significant ANOVA in order to explore the data further, since this was preliminary pilot data and the ANOVAs were underpowered. Standard F and t statistics are reported in the Results portion along with p-values.

3 Results

3.1 Exercise Physiology and Task Performance

To confirm the efficiency and intensity of the exercise manipulation, mean heart rate was calculated for each condition. Heart rate data for all conditions was collected from 6 out of 11 participants. The HR monitor became disconnected in one of the condition, most often in the resting condtition, for the remaining 5 participants, so they were excluded from this processing. The mean HR data at rest = 72.88 bpm, low cadence = 101.48 bpm and high cadence = 105.20 bpm (Figure 3A). A significant difference was found between the rest condition and exercise conditions [$F(2,17) = 4.65$, $p=.03$] but heart rate did not differ significantly when comparing the exercise conditions [$t(5) = 2.57$, $p=.15$].

Data for pedaling speed or cadence was processed from the start of the visual discrimination task and until 360 unbroken trials were finished. Mean measured cadence was 53.7 rpm and 72.6 rpm for the exercise conditions, low cadence (50 rpm) and high cadence (70 rpm), respectively (Figure 3B).

Mean time spent completing the orientation discrimination task across conditions was rest = 35.3 min, low cadence = 33.5 minutes, high cadence = 35.1 minutes.

Self-reported perception of exertion on the Borg RPE scale (see Appendix) did not differ significantly between conditions, with participants reporting on an average RPE = 6.16 in the resting condition, RPE = 7.44 for the low cadence and RPE = 7.625 for the high cadence, or no exertion to very light exertion.

The graph of the task performance data, seen in Figure 4, suggests that performance is slightly higher in the resting conditions and decreases with a faster cadence, but the difference is not significant. ANOVA reveals no differences between the conditions in performance [$F(2,20) = 2.11$, $p=.14$]. Pairwise comparisons also reveal no significant differences.

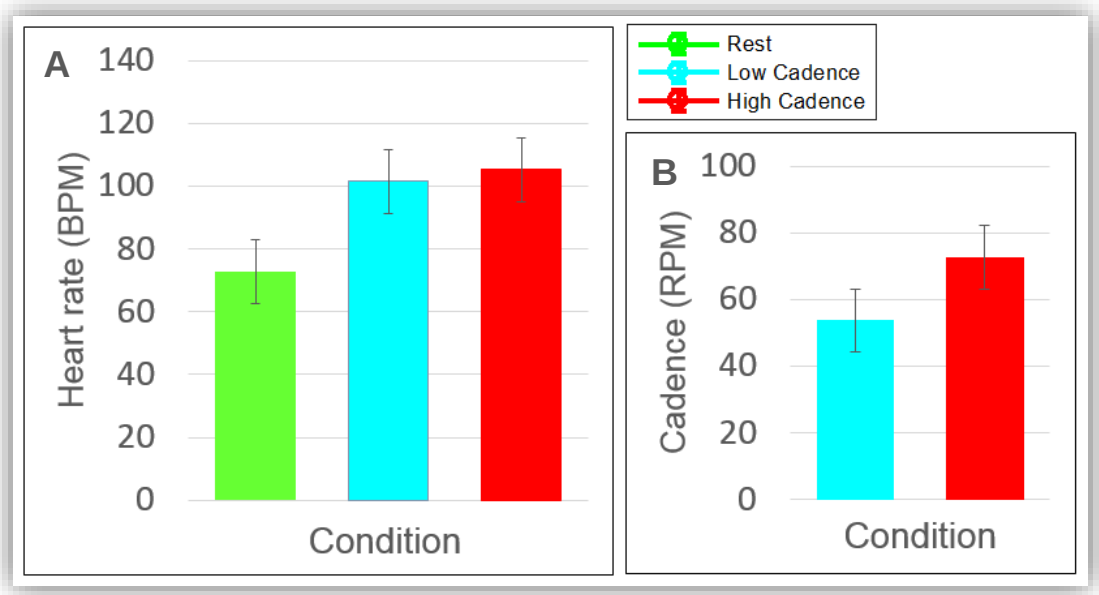

Figure 3: (A) Average HR across the conditions. HR in the exercise condition significantly higher compared to rest. (B) Average cadence of the exercise conditions, slightly faster than the goal cadence in each condition.

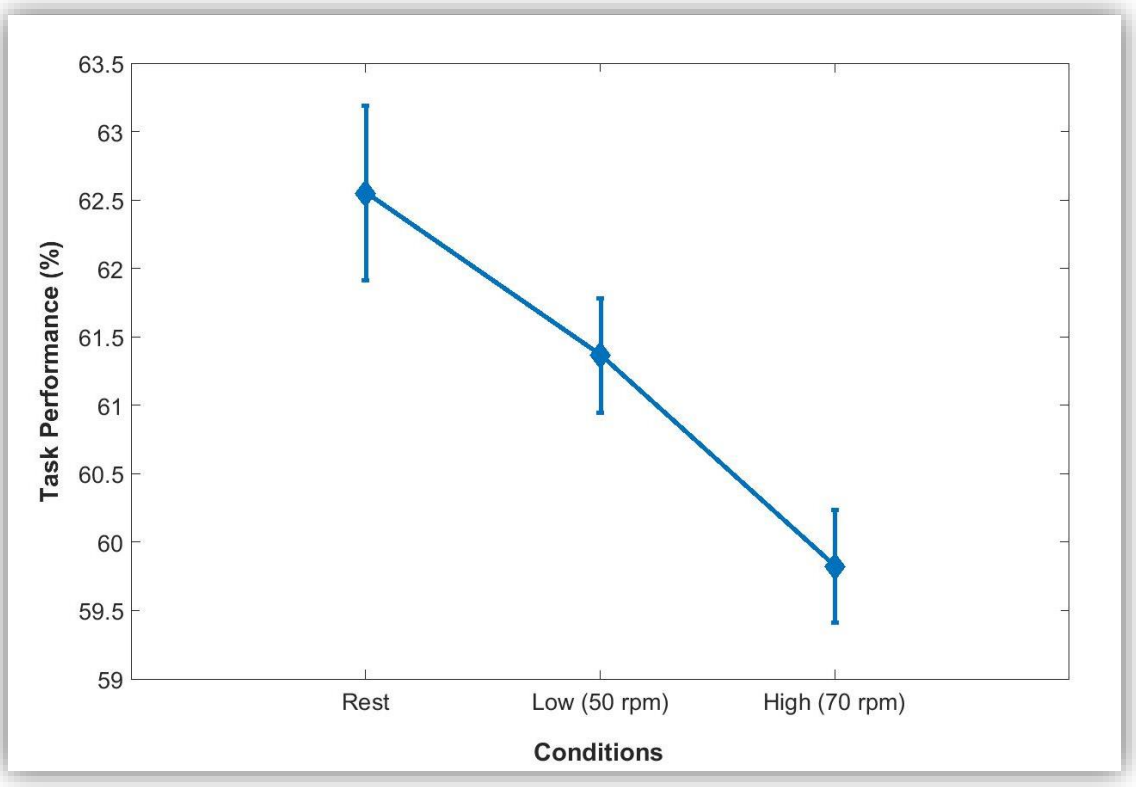

Figure 4: Behavioral performance in each condition with error bars

3.2 EEG power and Pattern Classification

After preprocessing the EEG data, a single-trial power between 4 and 20 Hz was estimated by using a fast Fourier transform in MATLAB. The stimulus flickered at 15 Hz, stream on/off on a blank grey screen and evoked a robust spike in power (μV^2) at the 15 Hz, the stimulation frequency, confirming that the visual stimuli worked as it is supposed to (Figure 5B). The mean brain activity from electrodes distributed focally at the occipital and parieto-occipital part of the brain was increased in all three conditions (Figure 5A). Mean power at 15 Hz was not significantly modulated by exercise intensity [$F(2,20) = 2.61$, $p=.09$] when all conditions were compared, but the p-value is trending towards significance ($p=.05$). However pairwise t-test suggest marginally significant differences between rest and low cadence (50 rpm) [$t(10) = 1.92$, $p=.08$] and significant differences between rest and high cadence(70 rpm) [$t(10) = 2.32$, $p=.04$] but no difference between the exercise conditions [$t(10) = .53$, $p=.61$].

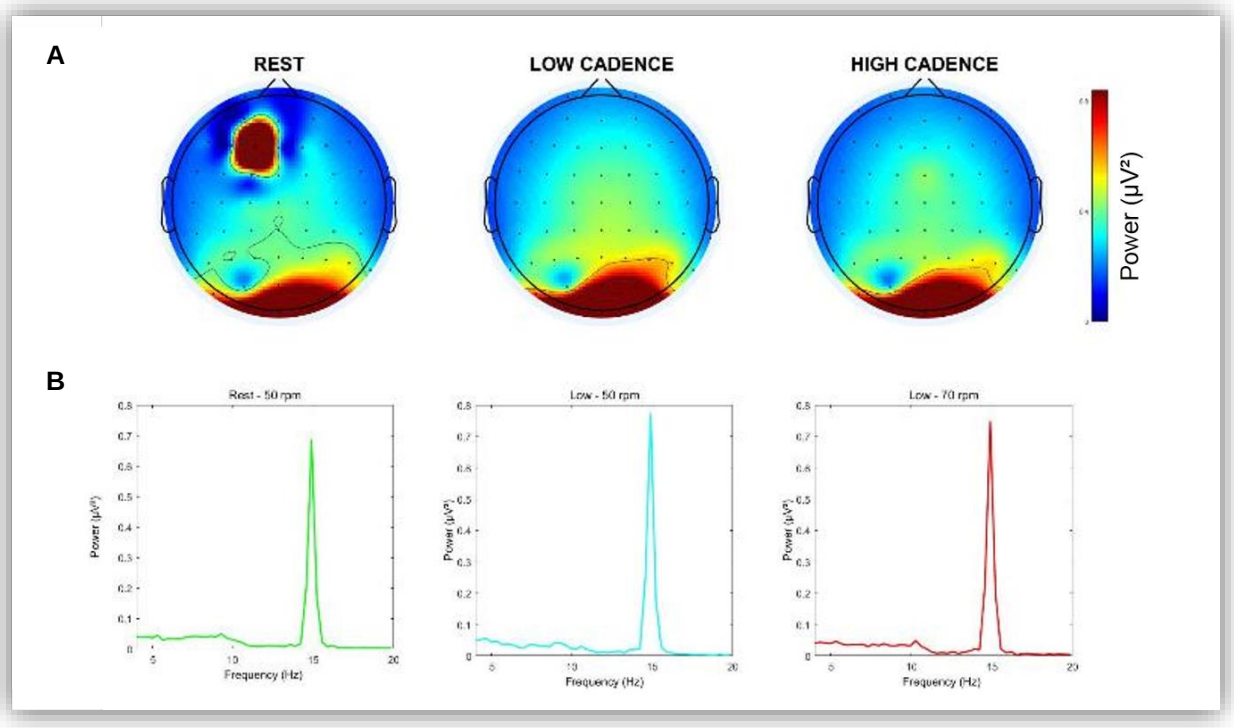

Figure 5: (A) Steady-state responses over the scalp recorded with the EEG. Most activity at occipital and parieto-occipital electrodes where the visual cortex is located. In the rest condition there is an unexplained peak in activity at the frontal electrodes. (B) A robust peak at 15 Hz seen in every condition.

3.3 Inverted Encoding Model

An IEM modeling technique (see methods) was used to reconstruct a tuning curve from the different patterns of spatial activation across cortex that are evoked in response to each of the different orientations. Two seconds of each trials were processed from artifact-free electrodes. All trials except one were used to make a training set, which was used to estimate the magnitude of the neurons response at each electrode as a linearly weighted sum of an idealized set of orientation tuning function, the basis set (Figure 6A). Then the training set was compared to the one trial left out to estimate the sensory evoked response from populations of neurons specifically tuned to different orientations. This process was repeated until all the trials had served in the training set as well as the trial being compared to the training set. An average of the channel responses was converted to power by taking the square of the absolute value of the complex numbers. These means are called channel tuning functions (CTFs) and are expressed as a term of power (μV^2). The CTFs for the evoked response at 15 Hz were then collapsed across each condition for each orientation and then centered at the 0 degrees. Plotted CTFs for the evoked response are seen in Figure 6 A & B. When comparing all conditions together ANOVA revealed no statistical difference between exercise and channel response [$F(8,80) = 1.86$, $p=.16$].

However, when looking at Figure 6B the curve is peakiest or greatest in the low cadence condition and the error bars are not overlapping with the error bars in the rest condition. This difference is confirmed when pairwise comparisons reveal significant difference between rest and low cadence at the CTF peak (0 degrees), [$t(10) = 2.28$, $p=.045$].

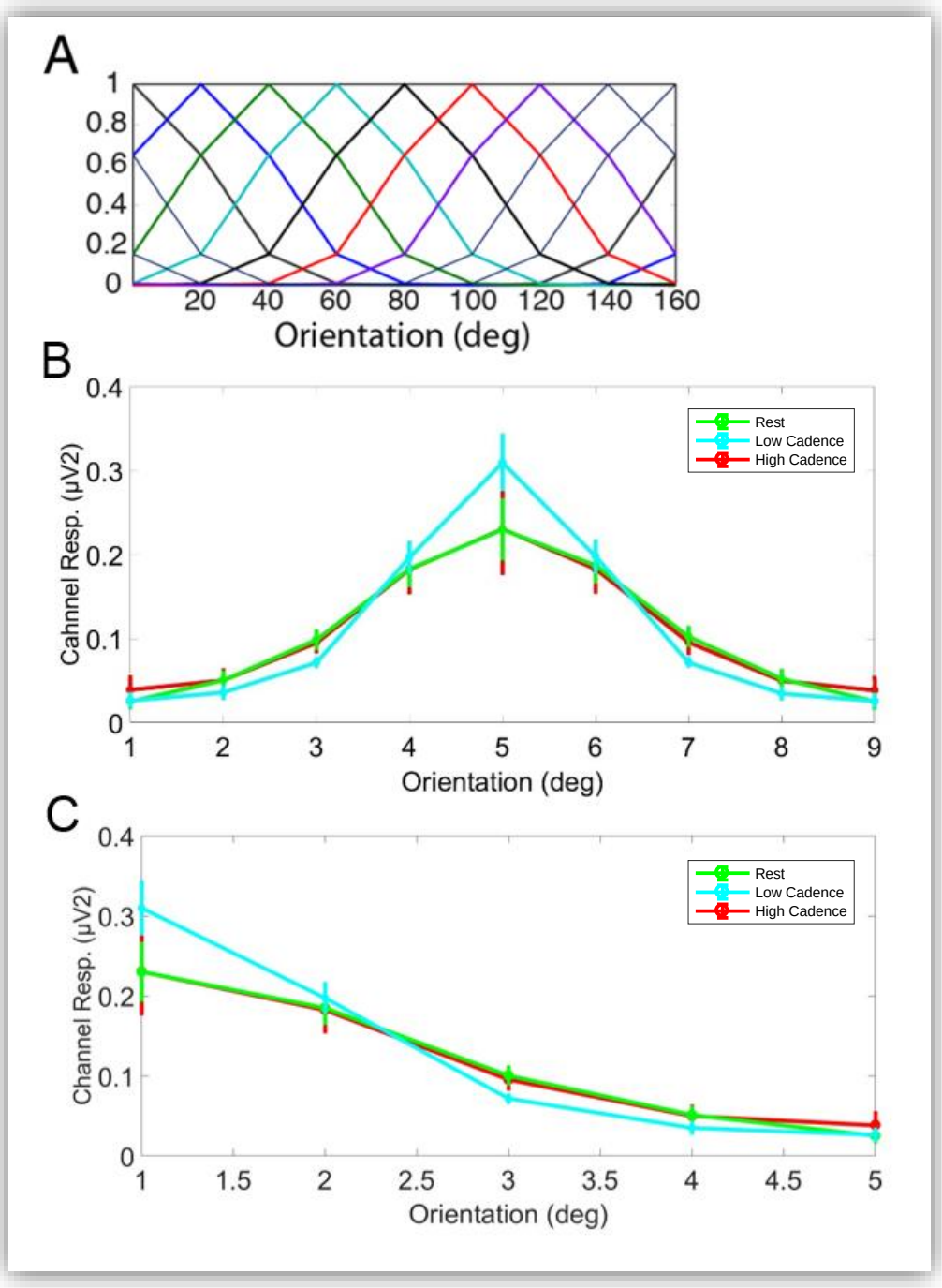

Figure 6: (A) The basis set with 9 basis functions from 0° to 160°**,** with 20° in between, raised to the seventh power yielding optimal tuning curves for each orientation. Figure from Bullock et al. 2017 (B) Centered channel tuning responses/functions collapsed across exercise conditions, for each condition. (C) Centered channel tuning functions folded from 9 points to 5 points to get more statistical power.

4 Discussion

The behavioral state of an animal affects the way that certain neurons in the visual cortex respond to different features of the visual environment. The focus of this experiment was on neurons in the human visual cortex selectively tuned to different orientations and what possible effect a change of behavioral state induced by physical activity would have on that response. Since a correlation of low intensity exercise and an increase in feature selective responses has been reported (18), that was the topic of interest. Responses were compared between two different pedaling speeds and rest with toe tapping. As previously reported, low intensity exercise seems to affect the tuning profiles of the evoked response by increasing the gain in response, with significant difference between rest and low cadence at 50rpm. However, the sample size was small, n=11, and therefore not enough statistical power for statistical significance was found through data processing. Based on previous research, we predict that the results, which trend toward significance, will reach it with a sample size of n=18.

The data from the electrodes placed on the scalp with the EEG measured the most activity at the occipital lobe, meaning the visual stimuli activated neurons in the visual cortex, as expected. The visual stimuli also evoked a robust response at 15 Hz, the stimulation frequency, verifying that the evoked response seen in the data are a response to the visual stimuli. This together verifies that the visual stimuli are working to the extent that they are evoking a steady state response in the neurons in the visual cortex. While there is no measured statistical difference when activity at all conditions is compared, the values are trending toward significance, and would likely reach significance with an increased sample size (n=18). This trend is enhanced due to the significant difference between rest high cadence. The comparison of activity during rest and low cadence is trending toward significance, but there is likely no significant difference between the two exercise conditions.

When looking to see if there was an effect on the evoked feature selective response in groups of neurons, the tuning functions were plotted with the IEM method with results showing a tuning curve in every condition. When comparing all conditions, no statistical difference was detected but when comparing two conditions at a time together a significant difference is seen between rest and low cadence. These results are aligned with earlier results where low intensity cycling at 50 rpm increased the response compared to rest and high intensity cycling. Increased tuning as a function of exercise is further confirmed by the non-overlapping error bars at rest and low cadence. At the same time the overlap of error bars, indicating non-significant difference, in the rest and high conditions is probably what is causing the ANOVA to come out non-significant. With more participants, the effect of low cadence cycling on neuron response would be expected to become more clear, with ANOVA reaching significance.

Earlier experiments have suggested that performance seemed to decrease with more intensity during exercise, with the best results occurring during the rest condition. However, these participants sat on a stationary bike during the rest condition and then performed the task while biking during the exercise condition. The question was that since the resting condition is a single task and the exercise conditions are dual task, with participants required to pedal to a beat at the same time as answering the visual

discrimination task. To correct for that difference in this study, the participants tapped their toes to the same beat as the low cadence speed, thus performing a dual task during the rest condition. The performance data does not show a significant difference between conditions. This might change with more participants but there is also a possibility that the performance numbers are reporting a different response than the tuning profiles. The tuning profiles measure the encoding for the response to one of the nine orientations represented in the task while the performance numbers are based on how well one detects a shift from that orientation. In theory, if the neurons are more attuned to a certain orientation, they should be more attuned to a shift in the orientation, however this might not be the case and therefore the detected increase in gain of neuron responses would maybe not translate into better performance at this task.

When studying the different cadences, 50 rpm appears to enhance the reconstructed tuning profile at the preferred orientation, suggesting that cadence may not be the primary contributing factor to neuron response at low intensity. This does contradict findings from earlier research, which suggested that increases in pedaling speed were linked to increases in response. It should be noted that a cadence of 50 rpm may have been a bit slow, as participants had the tendency to exceed 50rpm with a mean cadence of 53.7 rpm. Similarly, a cadence of 70rpm may have proven to be too fast. Though the mean cadence was 72.6 rpm, participants had a harder time keeping a steady pace and reported a slightly higher rate of perceived exertion (RPE) than during the low cadence.

In order to effectively measure the effect of any exercise on brain activity, steps must be taken to try to minimize any noise in the data. This is done here by stabilizing equipment to minimize upper body movement for the EEG recordings and using the eye tracker to keep people in place. Moving forward, it would be interesting to study experienced cyclists in in order to measure a wider range of cadences, as 50rpm and 70rpm appeared to be too slow and too fast respectively for inexperienced cyclists. Managing comfort is also a significant part of an experiment like this, as sitting on a bike for extended periods of time can prove to be very challenging. This is another reason that it would be interesting to study experienced cyclists, as they are accustomed to spending long durations on a bike.

This research is interesting as it seems to replicate earlier results of low cadence cycling increasing selective responses in the brain when compared to rest. It also serves as an important part of continuing to research what happens when humans engage in physical activity, shedding light on the cognitive impacts of exercise.

To summarize, this study used an IEM method to look at recorded EEG in rest and during exercise to investigate the influence of different behavioral states on the tuning profiles of sensory evoked responses in the human sensory cortex. The findings indicate that a change in behavioral state as a function of exercise influences these responses, and that low intensity exercise at 50 rpm cycling increases gain in selective responses. However, the sample was limited and more participants will be needed to get concreate and statistically significant responses.

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Appendix

BORG 6-20 Rate of Perceived Exertion Scale (RPE)		
No Exertion	6	Little to no movement, very relaxed
Extremely Light	7	Able to maintain pace
	8	
Very Light	9	Comfortable and breathing harder
	10	
Light	11	Minimal sweating, can talk easily
	12	
Somewhat Hard	13	Slight breathlessness, can talk
	14	Increased sweating, still able to hold conversation but with difficulty
Hard	15	Sweating, able to push and still maintain proper form
	16	
Very Hard	17	Can keep a fast pace for a short time period
	18	
Extremely Hard	19	Difficulty breathing, near muscle exhaustion
Maximally Hard	**20**	**STOP exercising, total exhaustion**