Interindividual Differences of Inhibitory Control in Healthy Young Adults: The Theta/Beta Ratio as Potential Neural Marker

Leonie Schulze (2027417)

Tilburg University

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Dr. Jeroen Stekelenburg

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Abstract

The current study investigated the potential of the resting state EEG theta/beta ratio (TBR) as neural marker for interindividual differences of inhibitory control skills in healthy individuals. It was hypothesized that that TBR would be negatively correlated to both subcomponents of inhibitory control, namely interference control and response inhibition (hypothesis 1 and 2) and additionally to a common inhibitory control score consisting of all outcome measures combined (hypothesis 3). Thirty-five healthy young individuals participated in the study and performed the Stroop and go/no-go task. Additionally, resting state EEG was recorded 5 minutes with closed eyes and 5 minutes with open eyes. Interference control was measured by the Stroop interference score and Stroop accuracy rate, and response inhibition was measured by the no-go error rate. Common inhibitory control was derived from the averaged z-scores of these outcome measures. Pearson correlations were performed between TBR and the 4 previously mentioned outcome measures, separately for TBRs derived from eyes open, eyes closed, and eyes aggregated recordings. It was corrected for multiple comparisons. Contrary to the expectations, no correlations were significant, showing that TBR could not predict interindividual differences in inhibitory control. It was therefore concluded that TBR could not serve as neural marker for inhibitory control skills in healthy adults.

Introduction

Executive functions (EFs), a group of top-down cognitive processes, are relevant to nearly every aspect of life (Diamond, 2013). Impaired EFs are not only related to mental health problems such as addiction (Baler & Volkow, 2006), depression (Taylor-Tavares et al., 2007), or attention-deficit-hyperactivity-disorder (ADHD; Lui & Tannock, 2007), but also to decreased physical health (Crescioni et al., 2011; Miller et al., 2011), reduced job success (Bailey, 2007), and diminished public safety (Broidy et al., 2003; Denson et al., 2011). Overall, individuals with better EFs experience a healthier and qualitatively better life (Brown & Landgraf, 2010; Davis et al., 2010). The main purpose of EFs is choosing and maintaining the most appropriate behavior to reach goals in situations where automatic actions are counterproductive (Miller & Cohen, 2001; Salehinejad et al., 2021). EFs are therefore effortful, active processes that require concentration (Diamond, 2013). They can be categorized into three core EF-modules – inhibitory control, working memory, and cognitive flexibility – that each encompass specific cognitive functions (Salehinejad et al., 2021), however, this paper will only focus on the first core module. Inhibitory control is defined as the ability to guide one's actions, attention, thoughts, or emotions in a way that automatic reactions are not elicited by internal or external cues but overridden and replaced by more appropriate behavior (Diamond, 2013). Moreover, the two subcomponents of inhibitory control are interference control and response inhibition (Diamond, 2013). Interference control specifically concerns attention and the ability to focus on certain aspects stimuli while supressing others. It is also called selective or focused attention, attentional control, or attentional inhibition (Diamond, 2013; Tiego et al., 2018). The second subcomponent of inhibitory control is response inhibition which is especially involved in controlling motor responses to specific stimuli. Interchangeable terms are behavioral inhibition, motor inhibition, or prepotent response inhibition (Tiego et al., 2018). Although inhibitory control is divided into two subcomponents, they have been found to correlate strongly (Friedman &

Miyake, 2004), meaning that they reflect different aspects of the same cognitive function. Thus, inhibitory control is a mechanism belonging to the EFs, used to strategically guide attention or motor responses in a goal-relevant way. The ability to exert inhibitory control differs between individuals and can be improved by training (Diamond, 2013). However, despite the relevance of EFs for the quality of life, not much is known about underlying reasons for individual differences in healthy individuals. It is therefore the aim of this thesis to explain individual differences in one of the core EFs, namely inhibitory control, by means of a neural marker. Individual levels of inhibitory control skills will be derived using two experimental tasks.

It has been suggested that inhibitory control is closely related to two complementary neural systems (Bishop, 2008). One the one hand, there is the "top-down" control system, which is also called endogenous or goal-directed control, responsible for actively guiding attention to goal relevant stimuli and is therefore internally induced. On the other hand, there is the "bottom up" control system, also called exogenous or stimulus-driven control, as it automatically processes salient stimulus features and is therefore externally induced (Bishop, 2008; Katsuki & Constantinidis, 2014; Kim & Cave, 1999). Both systems work reciprocally to each other, and exertion of inhibitory control requires a strong top-down system, which suppresses the activity of the bottom-up system (Bishop, 2008). Hence, the interaction of top-down and bottom-up systems determines how well inhibitory control can be exerted and task relevant features can be attended to (Connor et al., 2004). Evidence suggests that cortical areas, especially the prefrontal cortex (PFC), are involved in exerting top-down control (Buschman & Miller, 2007; Miller & Cohen, 2001; Rossi et al., 2009) and subcortical areas, especially the limbic system, are involved in the automatic bottom-up processing of salient stimulus features (Bishop, 2008; Knyazev, 2006). Thus, on the neurophysiological level, inhibitory control can be understood as the cortical regulation of subcortical processes.

Assessment of inhibitory control performance is commonly done with experimental tasks. The Stroop task, the flanker task, and the anti-saccade task assess interference control by requiring participants to attend certain characteristics of stimuli while having to ignore other goal-irrelevant aspects (Diamond, 2013). In the Stroop task, stimuli are words of colour names (e.g. “red”, “green”, “blue”, “yellow”) presented in coloured font that either matches the colour name (= congruent condition) or differs from the colour name (= incongruent condition). The participants’ task is to name the font colour of the coloured words. Interference happens in the incongruent condition, when the processing of one stimulus feature, namely the colour, is affected by the simultaneous processing of a different stimulus feature, namely the word meaning. Interference control requires suppression of the relatively salient stimulus feature “word meaning” while focusing on the colour of the word (Stroop, 1935). The reaction time (RT) difference between the congruent and the incongruent condition is known as the Stroop effect. During (a variation of) the Flanker task, five arrows are presented on screen, and participants must report the direction of the central arrow, ignoring the surrounding arrows. Interference control is required when the central arrow points in the opposite direction compared to the peripheral arrows, resulting in a RT difference between incongruent and congruent conditions (Eriksen & Eriksen, 1974). The anti-saccade task requires participants to inhibit the automatic tendency to look towards a stimulus and do the opposite instead (Munoz & Everling, 2004). Response inhibition can be measured by the go/ no-go task and the stop-signal task. During both tasks, the participants must respond or inhibit a response depending on which stimulus is displayed. The difference between both tasks is that in the go/no-go task, one stimulus is presented each trial, either the “go” or the “no-go” stimulus (Gordon & Caramazza, 1982). In the stop signal task, the go stimulus is displayed during every trial and followed up by a stop signal during no-go trials. Response inhibition is needed during no-go trials when the prepotent motor response must be inhibited (Logan & Cowan, 1984). The goal of all five tasks is to respond as quickly and

accurately as possible. Thus, shorter RTs (or smaller Stroop or flanker effects) and higher accuracy rates are indicative of better inhibitory control.

Inhibitory control performance varies substantially between individuals, and the most common method to study this has been the experimental method (Goodhew & Edwards, 2019). Researchers manipulate (or quasi manipulate) a variable of interest in the experimental group and measure its effect on inhibitory control performance. For instance, after engaging in physical exercise, students have a smaller Stroop effect (Fujihara et al., 2021; Kaya & Alpozgen, 2022) and smaller RTs on the flanker task (Shigeta et al., 2021) compared to before working out. Similarly, meditation (Fan et al., 2014) and yoga (Sharma et al., 2020) decrease the Stroop effect. Moreover, prophylactic naps lead to shorter RTs on the flanker task (Tanabe et al., 2020) while sleep deprivation increases RTs during a go/no-go task (Hudson et al., 2020; Skurvydas et al., 2021). On the other hand, substance use like high doses of caffeine lead to longer RTs on the Stroop task compared to controls (Foreman et al., 1989). Additionally, regular alcohol consumption causes worse performance on the go/no-go task, namely decreased RTs in the go condition and reduced accuracy in both conditions, which indicates a speed-accuracy trade-off (Zhao et al., 2017). Chronic pain however, decreases the Stroop effect compared to students without chronic pain (Hollins et al., 2020), and students with internet addiction disorder have a larger Stroop effect as well as lower accuracy rates than the control group (Dong et al., 2011). Hence, based on the above-mentioned examples, performance on inhibitory control tasks varies and is influenced by external factors.

Due to these findings, an emerging question is whether there are intrinsic, biological factors that explain individual differences with regard to inhibitory control skills. The relationship between underlying biological factors and these individual differences cannot be demonstrated using experimental manipulations, which were previously discussed to show the existence of group differences. To detect this relation, researchers are not interested in

significant averages between groups, but in systematic variations of performance within groups (Goodhew & Edwards, 2019). Therefore, researchers have adopted an individual differences (or correlational) approach during the last years, which aims to explain these between-participant deviations with variables intrinsic to individuals (Goodhew & Edwards, 2019), for example brain activity at rest. The goal of the current study is to find a neural marker of inhibitory control by means of the individual differences approach.

Resting state EEG (RS-EEG) or spontaneous EEG is a common method used to measure electrical activity in the brain at rest. With electrodes placed on the scalp, EEG captures post synaptic potentials of thousands of neurons with similar spatial orientation (Nunez & Srinivasan, 1981). The obtained signal is a complex wave that is decomposed during analysis into sine and cosine waves of different frequencies (Sawant & Jalali, 2010). These are commonly categorized into five frequency bands: delta (1-3 Hz), theta (4-7 Hz), alpha (8-12 Hz), beta (13-30 Hz). and gamma (>30 Hz). Based on these frequency bands, different measures can be calculated to quantify neural activity, for instance spectral power, hemispheric asymmetries or coherence, and frequency band ratios (Kim & Im, 2018).

Several RS-EEG measures have been investigated as neural markers for inhibitory control, but many of them have yielded inconsistent results. For instance, Fan et al. (2014) has reported a positive correlation between alpha power and performance on the Stroop task, while Schiller et al. (2014) has reported a negative correlation for the same RS-EEG measure with performance on the go/ no-go task, and Gordon et al. (2018) has found no relationship between alpha oscillations and performance on the anti-saccade task. Similar contradictory findings exist for delta power (Karamacoska et al., 2019; Karamacoska et al., 2018; Schiller et al., 2014) and hemispheric asymmetry of the beta/alpha ratio (Ambrosini & Vallesi, 2017; Gordon et al., 2018), each in relation to interindividual differences in inhibitory control. However, there has been a line of research supporting a relationship between theta/beta ratio (TBR) and inhibitory control. Angelidis et al. (2016), Putman et al. (2014), and Putman et al.

(2010) investigated whether TBR predicts individual differences in inhibitory control in healthy university students. Resting state EEG was recorded for “eyes open” and “eyes closed” conditions, alternating every minute for 8 minutes in total. All three studies used the self-report measure “Attentional Control Scale” (ACS) to measure inhibitory control. Putman et al. (2010) additionally assessed inhibitory control with an emotional go/ no-go task. Correlations were calculated between TBR and scores on inhibitory control outcome measures. Results of all three studies showed a negative correlation between TBR and ACS scores, or TBR and performance on the go/no-go task, suggesting TBR as neural marker for inhibitory control skills in healthy students. However, counterevidence exists as well. Morillas-Romero et al. (2015) investigated TBR in relation to attentional control using a similar design. Attentional control was measured by ACS and the ‘Attentional Network Test for Interactions’ (ANT-I). No significant correlations were found between TBR and ACS or TBR and ANT-I scores, indicating a disagreement in the literature about the relationship between TBR and inhibitory control in healthy individuals. Thus, research on neural markers for inhibitory control in healthy young individuals has yielded contradictory findings for all tested RS-EEG measures. Nonetheless, TBR appears to be the most promising to predict individual differences, as its relation to inhibitory control could be replicated several times.

Furthermore, TBR has already been established as marker for inhibitory control in some developmental stages and psychopathological conditions (Knyazev, 2006), which additionally underlines the measure’s potential. On the one hand, research has shown that during normal development, inhibitory control skills improve (Clark, 1996), while simultaneously low RS-EEG frequencies (e.g. theta) decrease and higher RS-EEG frequencies (e.g. beta) increase (Clarke et al., 2001; John et al., 1980). Hence, the decrease of TBR has been identified as a marker for inhibitory control maturation during child development (Cai et al., 2021). On the other hand, elevated TBR was linked to ADHD, a psychopathology that encompasses deficits in inhibitory control (Ahmadi et al., 2020; Arns et al., 2013; Barry et al., 2002; Bresnahan &

Barry, 2002; Chabot et al., 2001; Huang et al., 2018; Zhang et al., 2019; Zhang et al., 2017). Thus, TBR's function as neural marker of inhibitory control has been supported in developing children and ADHD patients. The question remains whether this relationship also holds for healthy adults, meaning that ADHD patients are simply on the extreme end of the spectrum, or whether the relationship between TBR and inhibitory control is qualitatively distinct in ADHD patients.

In the ADHD population, evidence suggests that TBR reflects the interaction of the bottom-up and top-down systems in the brain that underly inhibitory control. ADHD symptoms, which are accompanied by elevated TBR, are thought to be a consequence of cortical hypoarousal and subcortical hyperarousal (Mayer et al., 2016; Rowe et al., 2005), so of insufficient top-down control and elevated bottom-up control. This is further supported by the evidence that administration of specific psychostimulants, which increase the activity in the PFC, decreases ADHD symptoms (Rajeh et al., 2017) and simultaneously normalizes TBR (Clarke et al., 2007; Clarke et al., 2002). A normalized TBR in this context means an increased relative contribution of the beta power and a decreased relative contribution of the theta power. Considering these findings, it is suggested that beta power reflects the activity of the top-down system, the theta power the activity of the bottom-up system, and TBR the degree of control of the former system over the latter (Angelidis et al., 2016). Even in healthy adults, beta power was related to inhibitory processes (Picazio et al., 2014; Waldhauser et al., 2012) and theta power to impulsivity (Knyazev, 2006). Thus, it is likely that TBR not only reflects cortical and subcortical interactions related to inhibitory control in ADHD patients but also in healthy adults.

The lack of research on healthy individuals' relationship between TBR and inhibitory control operationalized by task performance represents a gap in the scientific literature. Furthermore, the studies that have found consistent evidence for a relationship between TBR and inhibitory control in healthy individuals have all used the self-report measure ACS to

operationalize inhibitory control. However, concerns about the validity of ACS have been reported, as ACS scores failed to predict behavioral performance on the Attentional Network Test, a behavioral measure closely related to inhibitory control (Williams, 2017). Due to this lack of evidence for an association between the self-report measure and behavioral performance, the authors suggested to measure inhibitory control directly with tasks instead of the self-report measure ACS. The current study therefore aims to fill the gap in the literature by replicating the relationship between TBR and inhibitory control in healthy individuals, using performance-based behavioral measures. Especially the field of cognitive enhancement research would profit from the clarification of TBR's relation to inhibitory control in healthy adults, because TBR Neurofeedback has recently gained attention as tool for healthy adults (Doppelmayr & Weber, 2011; van Son et al., 2020).

In the current study, RS-EEG of university students was recorded for eyes open and eyes closed conditions and participants completed the Stroop and go/no-go tasks. It is hypothesized that RS-EEG TBR is negatively correlated to the interference control outcome measures of the Stroop task (hypothesis 1) and to the response inhibition outcome measure of the go/ no-go task (hypothesis 2). According to the "task-impurity" problem formulated by Miyake and Friedman (2012), each task also measures specific non-EF processes, which results in substantial measurement error. Therefore, a common inhibitory control score was calculated by combining the outcome measure of the Stroop and go/ no-go task into a composite score, as it was done by Zhang et al. (2018). It is hypothesized that TBR is negatively correlated to the common inhibitory control score (hypothesis 3).

Method

Participants

Thirty-five individuals (26 female, 9 male) aged 19 to 53 (M = 22.43 years, SD = 5.72 years) participated in the experiment. There was one outlier (age = 53 years) which was removed post data collection because it has been shown that TBR decreases with age (Maylor

et al., 2011), and age-related effects might distort the results. After exclusion, the data set consisted of 34 individuals (25 female, 9 male) aged 19 to 28 (M = 21.53 years, SD = 2.12 years). Twenty of the participants were Dutch (14 non-Dutch) and 28 were right-handed (5 left-handed, 1 unknown). An a priori power analysis was conducted to determine the minimum sample size required to answer the research question. Results showed that a sample size of N = 85 was necessary for Pearson correlations to detect a medium effect (r = .3) with 80% power at a two-tailed significance level of α = .05. The intended sample size was not reached. Participants were recruited via convenience sampling from the Dutch and international Psychology Bachelor's Program of Tilburg University and received 2 subject hours as reimbursement that counted towards the passing grade of a mandatory course. Some test leaders recruited additional participants from their circle of friends and acquaintances. All participants gave written informed consent and could withdraw from the experiment at any point without consequences. The study was approved by the Ethical Review Board of Tilburg University (Code: EC-2016.48a2, date: 13th December 2016) in accordance with the principles of the Helsinki Declaration.

Measures

Stroop task

The Stroop task (Stroop, 1935), a choice reaction time task, was used as measurement for interference control. The task was administered on a computer using the program "Open Sesame" (Mathôt et al., 2012). Stimuli were names of colours displayed in uppercase letters of font size 100 ("GREEN", "YELLOW", "BLUE", "RED") in the middle of the screen on a grey background. Four different font colours were used to print the stimuli, namely green, yellow, blue, and red. The task encompassed two stimulus conditions, namely congruent and incongruent. In the congruent condition, colour name and font of the stimuli matched (for instance, "yellow" displayed in yellow font). In the incongruent condition, colour name and font did not match (for instance, "yellow" presented in blue font). Each trial consisted of the

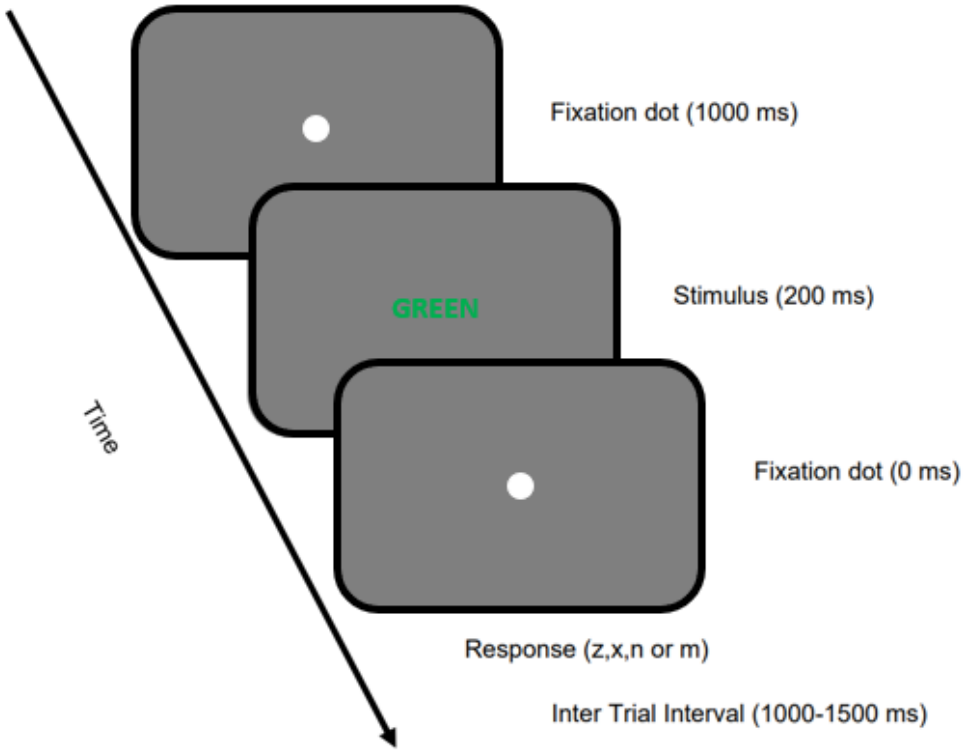
display of a fixation dot for 1000 ms, the stimulus for 200 ms, and an infinite response time. Participants had to report the font colour of the stimulus by pressing specific keyboard buttons ("z" for red, "x" for green, "n" for blue, and "m" for yellow). The next trial started on average 1250ms after a response has been given, with an inter trial interval (ITI) variating between 1000 and 1500 ms. An example trial is visualized in figure 1. In total, there were 3 blocks of 96 trials, each consisting of 48 congruent and 48 incongruent trials presented in random order. Before starting the task, participants had to complete two different practice sessions. First, a 100-trial mapping session was administered to learn which key stood for which colour (25 trials per colour). Stimuli were as many coloured uppercase "x" as letters in the corresponding colour name (green font = XXXXX, red font = XXX, yellow font = XXXXXX, blue font = XXXX). Participants were required to report the font colour by keyboard-press like in the actual experiment ("z" for red, "x" for green, "n" for blue, and "m" for yellow). Second, a 24-trial regular practice session (12 congruent and incongruent trials each) was completed to familiarize the participant with the experiment. Participants received two scores on each item of the Stroop task: RT in ms and response accuracy (true or false). The shorter the RT differences were between congruent and incongruent conditions (= interference), and the more correct responses, the better considered the participant's ability to supress task irrelevant information (= interference control). Hence, key indexes of interference control were Stroop interference score and accuracy rate.

The Stroop task version used in the current study was adapted from the original for completion on the computer without being validated. The interference score of the original Stroop task has been shown to have an 11-week test-retest reliability of .84 and an internal consistency reliability (Cronbach's alpha) of .93 (Wöstmann et al., 2013). Cronbach's alpha of the current sample was calculated as in Wöstmann et al. (2013) by dividing the task into 4 segments and deriving the interference score for each segment. Internal consistency over the 4 segments was then calculated with the Cronbach's alpha command in SPSS, which resulted in

a score of .72 for the present sample. However, a study investigating the validity of computerized Stroop task versions revealed poor convergent validity with the original Stroop task version (Penner et al., 2012).

Figure 1

Illustration of a trial in the Stroop task



Note. Adapted from *Specifications Method for Bachelor Thesis*, by Dept. Cognitive Neuropsychology, 2022, Tilburg University, p. 8.

Go/ no-go task

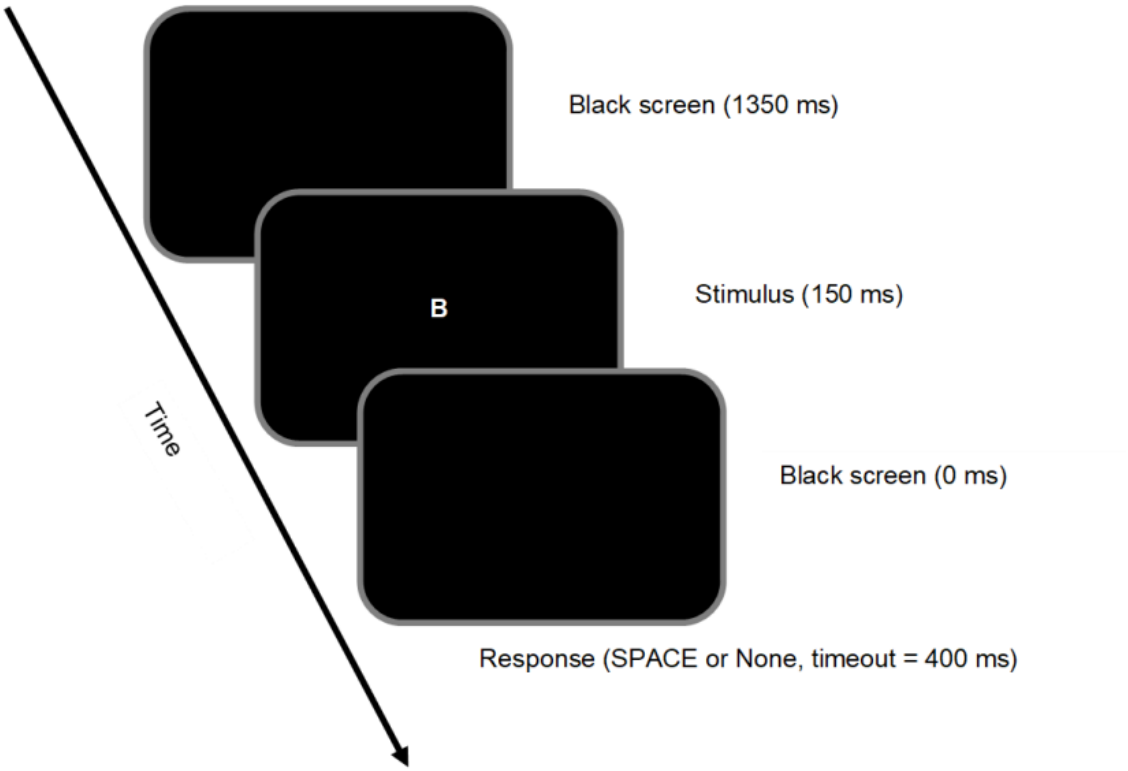
As measure of response inhibition, the go/ no-go task, developed in its original version by Gordon and Caramazza (1982), was used. The task was administered on the computer using the program Open Sesame (Mathôt et al., 2012). The stimuli were 5 upper case letters (“H”, “R”, “S”, “P”, “B”) in white font, presented on a black background in the middle of the screen. Each trial consisted of the display of a black screen for 1340 ms, followed by the stimulus for 150 ms, and a fixed response timeout of 400 ms. There were two conditions,

namely go and no-go. In the go condition, which encompassed all letters except “B”, participants were required to press spacebar by upon sight of the stimuli. When the letter “B” was displayed (= no-go condition), participants were instructed to withhold their response. An example trial is visualized in figure 2. Each unique stimulus was repeated 80 times, adding up to 320 go and 80 no-go trials (400 in total), presented in random order in four blocks of 100 trials. By including more go than no-go trials, pressing the spacebar became a prepotent response. Before the start of the real experiment, participants completed 10 practice trials to familiarize themselves with the task. Every item was either scored true or false. The lower the number of false responses in the no-go condition (= commission errors), the better considered the participants’ ability to withhold a prepotent response (= response inhibition). Hence, key index of response inhibition was the no-go error rate.

The computerized go/ no-go task used in the current study was adapted from originally oral responses to manual keyboard responses without being validated. Similar computerized go/ no-go tasks have been shown to have a test-retest reliability of .56 (Tyburski et al., 2021) or .65 (Weafer et al., 2013) and an internal consistency (Cronbach’s alpha) of .87 (Wöstmann et al., 2013). Cronbach’s alpha of the current sample was calculated as in Wöstmann et al. (2013) by dividing the task into 4 segments and deriving the no-go error percentage for each segment. Internal consistency over the 4 segments was then calculated with the Cronbach’s alpha command in SPSS, which resulted in a score of .92 for the present sample. A validation study investigating the construct validity of computerized go/no-go task has provided evidence that the nogo error rate indeed measured response inhibition (Tyburski et al., 2021).

Figure 2

Illustration of a trial in the go no go task



Note. Reprinted from *Specifications Method for Bachelor Thesis*, by Dept. Cognitive Neuropsychology, 2022, Tilburg University, p. 11.

Resting state EEG recording

For the EEG recording, the Active two device (BioSemi, Amsterdam, The Netherlands) was used with a sampling rate of 512 Hz. In total, 42 Ag/AgCL electrodes were installed. 32 EEG pin electrodes were attached to an elastic cap using the international 10/20 system. The online reference electrode (CMS: Common Mode Sense) was placed between Cz and C3 and the ground electrodes was located between Cz and C4. 8 flat sensors were placed on the face and body collecting reference, EOG (detecting horizontal and vertical eye movements) and ECG signals. More specifically, they were applied to left and right mastoid (for offline reference), laterally to each eye, above and below one eye (EOG), and to the central and left lateral ribcage under the armpit, within the same horizontal plane located two fingers above the sternum (ECG). The electrolyte gel “signa gel” from the brand “Parker” served as conductor between sensor and skin. The quality of the signal was considered sufficient when

the direct current offset lay below 50 mV. Resting state brain activity was recorded 5 minutes with eyes opened and 5 minutes with eyes closed. The task was to relax and think about nothing specific. During the eyes open condition, participants had to look at a fixation cross presented in the middle of the screen. In the eyes close condition, participants were verbally informed by the test leader about having reached the end of the task.

Procedure

The study consists roughly of four parts that participants ran through individually: informed consent, preparation, experiments, and filling in questionnaires. After the attachment of the sensors, participants were led into a sound attenuating and dimly lit cabin, where they took a seat behind a computer with approximate viewing distance of 60 cm. They were observed by the test leaders via CCTV. The experiments were run in a fixed order to minimize error due to participant by order interaction. First the Stoop task, second the go/ no-go task, third the IAPS task (used for a different study), and lastly the eyes open and eyes closed resting state recording was administered. After the experiment, the electrodes were removed, and the participants were asked to fill out questionnaires (used for a different study). In total, the experiment including attachment of sensors and completion of tasks and questionnaires took 2.5 hours.

Statistical analyses

Outlier removal

Outlier removal criteria were applied to Stroop RT data. Due to the nature of the task, outlier removal was not necessary for the go/ no-go data.

Data points below 150 ms were discarded due to the physiological lower limit of RT. Furthermore, individual cut off values were calculated for every participant based on their RT distribution. This was done using the method by Cousineau and Chartier (2010). First, RT distributions were transformed to resemble a normal distribution and z-scores were calculated. Second, data points above and below z-scores of +- 2.5, respectively, were removed, targeting

values within the outer 1.24 % of the area under the curve. An exception to this procedure was made. One participant had a normal RT distribution, so it was not transformed, and z-scores were calculated based on the original RT distribution.

On average, 0.8 % of the data points within the left tail and 1.6 % of the data points within the right tail were excluded. The average cut off values were 349.91 ms (*SD* = 48.89 ms) and 1977.25 ms (*SD* = 626.21 ms).

Resting State EEG pre-processing

EEG data were analysed using Brain Vision Analyzer 2.1 (Brain Products GmbH, Germany). EEG data were re-referenced offline to the average of both mastoids, filtered (low cut-off = 0.01 Hz, high cut-off = 60 Hz, and notch = 50 Hz), and artefacts due to eye movements were corrected using ICA. Then, eyes open and eyes closed segments were created relative to reference marker location, which were each further split into 4s sections with 50 % overlap. Within these 4s segments, voltage steps larger than 50 μV/ms or value ranges larger than 200 μV at any channel were considered artefacts due to movement or muscle activity and were removed for all EEG electrodes. Fast Fourier Transformation was applied to each segment (Hanning window length = 10 %), and the Welch spectra were calculated separately for eyes open and eyes closed conditions by averaging the data across the 4s segments (excluding the first two). Additionally, the eyes aggregated condition was created by averaging all Fast Fourier-transformed 4s segments, irrespective of condition. This was done because all previous studies, which investigated the relationship between TBR and inhibitory control, conducted their hypothesis tests on aggregated EEG data of eyes open and eyes closed recordings (Angelidis et al., 2016; Morillas-Romero et al., 2015; Putman et al., 2014; Putman et al., 2010). Finally, for each participant, the power densities of the theta (4-7 Hz) and the beta (13-30 Hz) band were extracted for all electrodes from the Welch spectra of all 3 conditions (eyes open, eyes closed, and eyes aggregated).

The test-retest reliability of TBR has been shown to be high, more specifically .93 (Angelidis et al., 2016). Split-half reliability of the current sample was generated for eyes open, eyes closed, and eyes aggregated. This was done by calculating the Welch spectra separately for even and odd segments in each condition and extracting the power densities (of 4 – 30 Hz) for every participant. Then, correlations were calculated between the power densities of even and odd segments in each condition, which were separately entered into the Spearman-Brown split-half formula. Split-half reliability of above 0.9 is considered high (Gordon et al., 2018). In all three EEG conditions, split half reliability was 0.99.

SPSS

Statistical analyses were conducted in Statistical Package for the Social Sciences (SPSS), release 25 (IBM Corp., Armonk, NY) and were divided into descriptive statistics and hypotheses testing. Beforehand, the variables of interest were calculated.

TBR was calculated by dividing theta power density through beta power density. There were three different resting state EEG conditions, namely eyes open, eyes closed, and eyes aggregated. Within these conditions, the electrodes were divided into 3 different regions, namely frontal (F3, Fz, F4), central (C3, Cz, C4), and parietal (P3, Pz, P4). Average TBRs were calculated per participant, for each region and condition. The Stroop interference score was calculated by subtracting congruent RTs from incongruent RTs and averaging it per participant. Only correct responses and data points not marked as outliers were used to calculate averages. The Stroop and no-go error percentages were calculated per participant by dividing the number of incorrect trials through the total number of trials for each task. The common inhibitory control score was calculated by converting each participant's raw average Stroop interference score, Stroop error percentage, and no-go error percentage into z-scores and taking the mean of the outcome measures. This score represents a measure of common inhibitory control ability across both tasks, while reducing the influence of task specific effects not due to inhibitory control (Miyake et al., 2012; Zhang et al., 2018).

Descriptive analyses were performed by deriving the mean and standard deviation of and correlations between all variables. All variables were checked for normality with the Shapiro-Wilk test to verify the normality assumptions of t-tests and Pearson's correlations. In case of non-normality, variables were log-normalized before hypothesis testing. Furthermore, t-tests were performed as manipulation checks between the conditions of the tasks.

To test the hypotheses, Pearson correlations were used. Each hypothesis associated resting state TBR with a different behavioral construct that was operationalized by one or two outcome measures. Interference control (hypothesis 1) was operationalized by the Stroop interference score and Stroop error percentage, response inhibition (hypothesis 2) was operationalized by the no-go error rate and inhibitory control (hypothesis 3) was operationalized by the common inhibitory control score. The three hypotheses were tested by correlating each region's (log-normalized) TBR with each (log-normalized) behavioral variable, while correcting for multiple comparisons (Bonferroni). This analysis was done separately for eyes open, eyes closed, and eyes aggregated. ECG data were not analysed.

Results

The obtained results were divided into two parts. The first part provided the results of descriptive analyses, which were performed to summarize the data and check for normality. Non-normally distributed variables were transformed by log-normalization, and transformed variables were denoted by the superscript "t". The second part provided the results of the hypothesis tests, which were all two tailed with a critical significance level of .05 if not stated otherwise. All hypotheses tests that included transformed variables yielded the same results for the corresponding untransformed variables.

Descriptive statistics

Behavioral data

Manipulation checks were performed by conducting a two-tailed paired samples t-test between the two conditions of each task. Because t-tests assume normally distributed data, the

data were checked for normality with the Shapiro-Wilk test before performing the manipulation check. Test statistics are reported in table 3. Due to non-normality, both Stroop conditions (congruent and incongruent RTs) were log-normalized. The error rates of the two go/no-go conditions could not both be transformed into a normal distribution due to differences in shape of the distributions. That is why untransformed data were used for the manipulation check of the go/ no-go task, despite non-normality of go error percentage. The manipulation checks revealed that that the Stroop average incongruent RT^{t}s were significantly larger (M = 837.37 ms, SD = 201.35 ms) than Stroop average congruent RT^{t}s (M = 727.51 ms, SD = 152.14 ms), $t(33) = 12.41$, $p < .001$. For interpretability reasons, descriptive statistics in brackets were reported for non-transformed data. The t-test comparing error percentage of the go (M = 4.72 %, SD = 6.13 %) and no-go condition (M = 25.51 %, SD = 12.32 %) was significant as well, $t(33) = 7.70$, $p < .001$. This shows that the intended manipulations were successful, which is essential to obtain meaningful outcome measures.

Central tendencies and variabilities of this study's measures of interest are displayed in their untransformed form in table 1. Shapiro-Wilk tests were performed to check for normality, test statistics are presented in table 3. Stroop interference score and Stroop error percentage differed significantly from normality. Error percentage of the no-go condition and the common inhibitory control score were normally distributed. Based on these results, Stroop interference score and Stroop error percentage were log-normalized before hypothesis testing. The spread of all outcome measures in their normally distributed form, which was used for hypothesis testing, is displayed in figure 3.

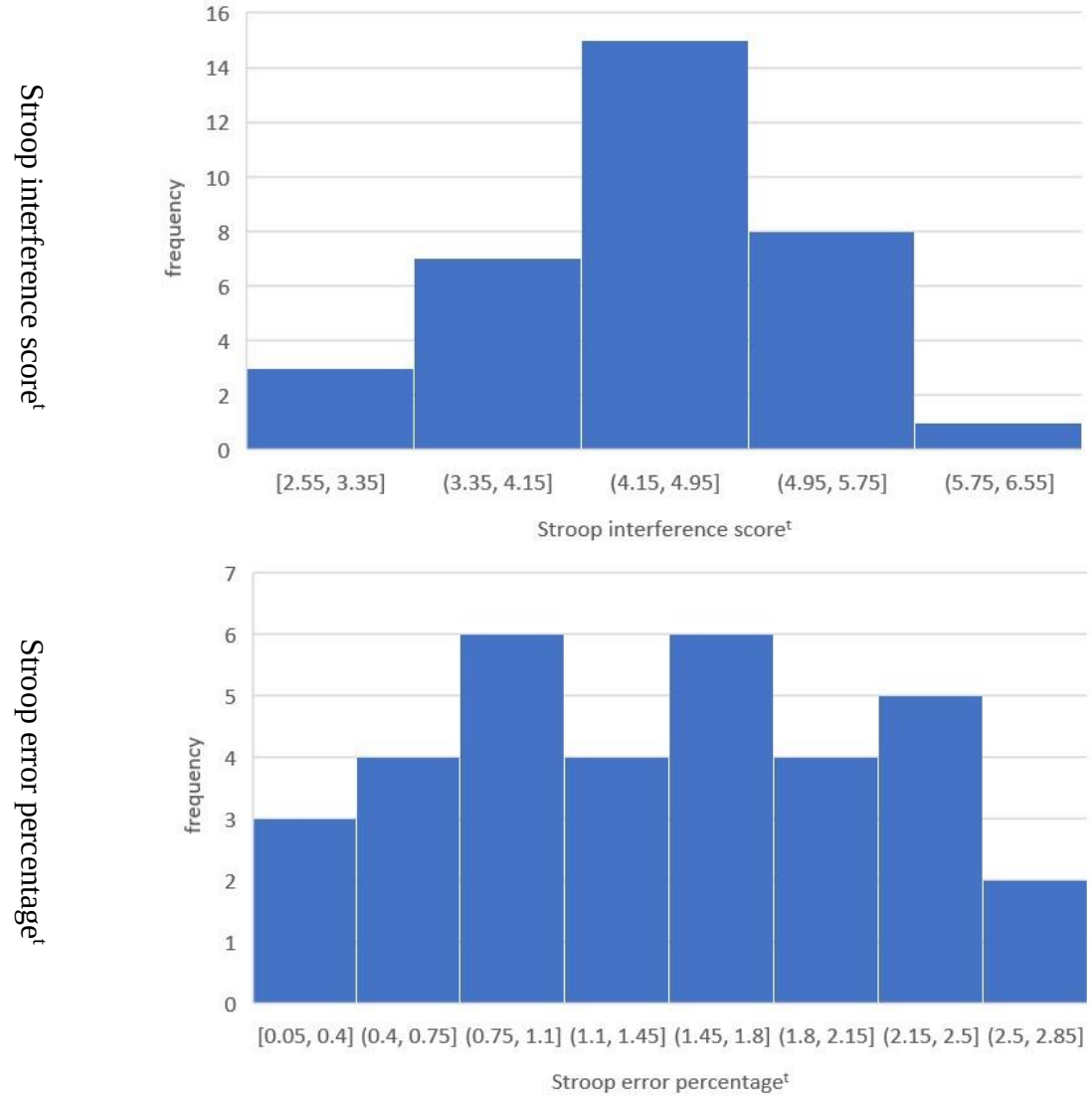
Table 1

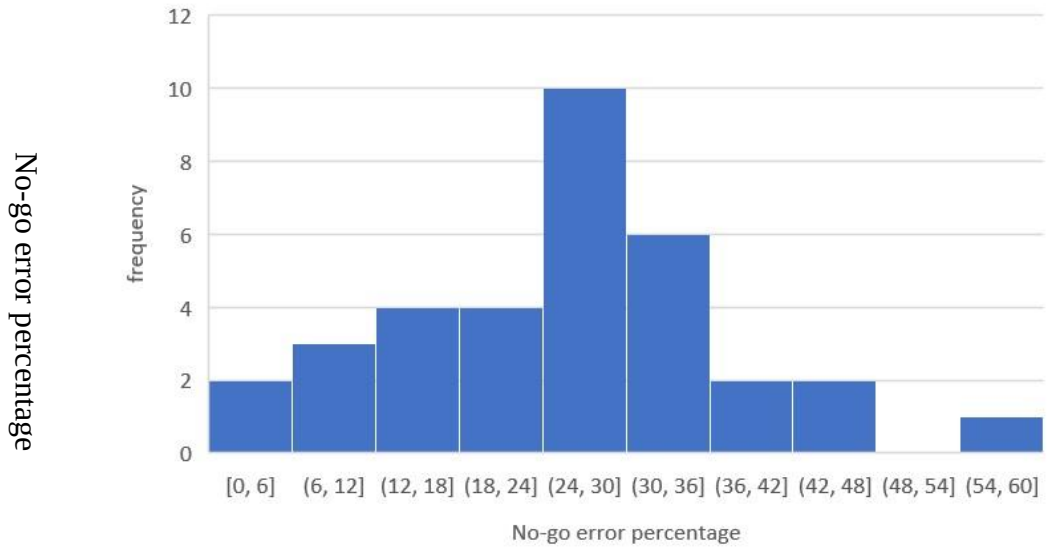
Mean scores and standard deviations of untransformed outcome measures across participants

Measure	*M*	*SD*
Stroop interference score	109.86 ms	70.62 ms
Stroop error percentage	16.79 %	5.24 %
No-go error percentage	25.51 %	12.32 %

Figure 3

Spread of outcome measures in the normally distributed form used for hypothesis testing





Note. Transformed measures have no particular unit.

[t] transformed measure

EEG data

As described earlier, each participant's average power spectrum (or Welch spectrum) was calculated by averaging the 4-second segments. Due to artefact rejection applied to these segments, a different number of segments was used per participant. On average, 139.88 (*SD* = 11.59) segments were used for participants in the eyes aggregated condition, 127.47 (*SD* = 26.20) in eyes open, and 124.26 (*SD* = 25.5) in eyes closed. Afterwards, theta and beta band average power densities were extracted per participant and TBR was calculated. Grand average TBR power densities across participants and *SD*s are displayed in table 2 for each region (frontal, central, parietal) and condition (eyes open, eyes closed, eyes aggregated) separately. TBR was the most pronounced centrally on the head, the topographies can be seen in figure 4.

Shapiro-Wilk test were performed to check for normality of TBR, the test statistics are reported in table 3. All TBRs were non-normally distributed and therefore log-normalized

before hypothesis testing. The distribution of the eyes aggregated parietal TBR was non-normal even after transformation.

Table 2

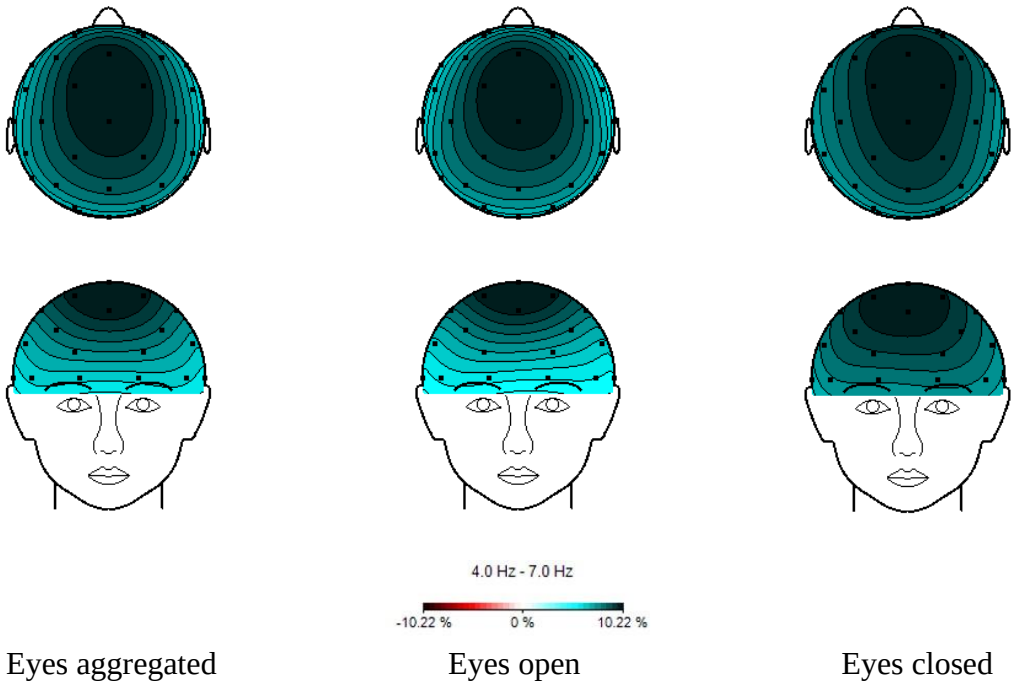
Means and standard deviations of theta/beta ratio power densities per condition and location

Condition	TBR		
	Frontal	Central	Parietal
Eyes aggregated	.32 (.26)	6.10 (3.14)	5.55 (2.96)
Eyes open	5.39 (2.92)	5.81 (2.65)	5.21 (2.35)
Eyes closed	7.11 (4.77)	6.80 (4.14)	6.22 (4.09)

Note. Standard deviations are presented in parentheses. Theta beta ratios and SDs are reported for non-transformed data. TBR= Theta/beta ratio.

Figure 4

Topography of theta/beta ratio per condition

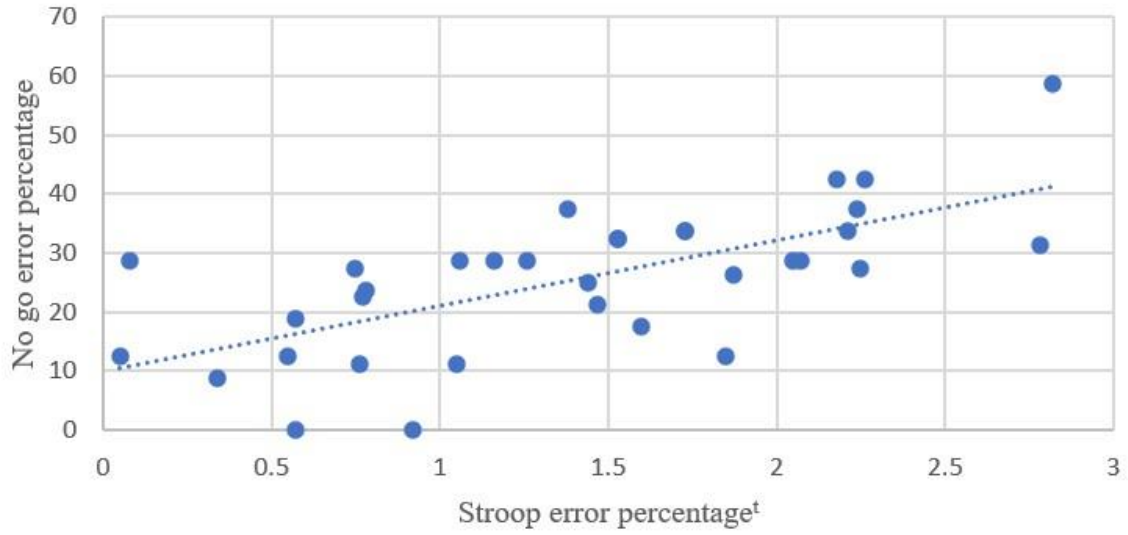


Correlations of each dependent variable pair

Pearson correlations were conducted between Stroop interference score^t and Stroop error percentage^t, $r(34) = -.03$, $p = .87$, Stroop interference score^t and no-go error percentage, $r(34) = -.29$, $p = .1$, as well as Stroop error percentage^t and no-go error percentage, $r(34) = .67$, $p < .001$. Only the correlation between the error percentages of Stroop and no go was significant, showing that error percentages on both tasks were positively related to each other. A scatter plot of the correlation is displayed in figure 5.

Figure 5

Scatter plot displaying the correlation between Stroop error percentage^t and no-go error percentage



Note. Transformed measures have no particular unit.

The influence of age

The influence of age was checked by correlating it with the independent and dependent variables. Age was not normally distributed, even after transformation (see table 4), which is why non-parametric Spearman correlations were used. These were calculated between age and Stroop interference score, $r_s(34) = .01$, $p = .95$, age and Stroop error percentage, $r_s(34) = -.18$, $p = .30$, age and no-go error percentage, $r_s(34) = -.04$, $p = .84$, age and common inhibitory control, $r_s(34) = -.08$, $p = .67$, and age and TBR^t (averaged over all electrodes). In the latter case, it was done separately for eyes aggregated, $r_s(34) = -.3$, $p = .86$, eyes open,

$r_s(34) = .08$, $p = .65$, and eyes closed, $r_s(34) = -.04$, $p = .82$. No significant association were found between the variables. Thus, age did not influence this study's variables of interest.

Table 3

Distributions of original and transformed variables based on Shapiro-Wilk test of normality

Variable	Before transformation[a]		After transformation[a]	
	Test statistic[b]	Distribution	Test statistic[b]	Distribution
Age	$W(34) = .46$, $p < .001$	Non-normal	$W(34) = .62$, $p < .001$	**Non-normal**
Stroop task				
RT congruent	$W(34) = .96$, $p = .32$	Normal	$W(34) = .97$, $p = .36$	Normal
RT incongruent	$W(34) = .92$, $p < .05$	Non-normal	$W(34) = .95$, $p = .11$	Normal
Interference score	$W(34) = .90$, $p < .01$	Non-normal	$W(34) = .96$, $p = .18$	Normal
Error percentage	$W(34) = .85$, $p < .001$	Non-normal	$W(34) = .97$, $p = .57$	Normal
Go/no-go task				
Error percentage go	$W(34) = .62$, $p < .001$	**Non-normal**	-	-
Error percentage no-go	$W(34) = .96$, $p = .29$	Normal	-	-
Eyes collapsed				
TBR frontal	$W(34) = .81$, $p < .001$	Non-normal	$W(34) = .97$, $p = .41$	Normal
TBR central	$W(34) = .85$, $p < .001$	Non-normal	$W(34) = .97$, $p = .53$	Normal
TBR parietal	$W(34) = .87$, $p < .001$	Non-normal	$W(34) = .93$, $p < .05$	**Non-normal**
Eyes open				
TBR frontal	$W(34) = .90$, $p < .01$	Non-normal	$W(34) = .98$, $p = .75$	Normal
TBR central	$W(34) = .91$, $p < .01$	Non-normal	$W(34) = .99$, $p = .95$	Normal
TBR parietal	$W(34) = .92$, $p < .05$	Non-normal	$W(34) = .98$, $p = .86$	Normal
Eyes closed				
TBR frontal	$W(34) = .81$, $p < .001$	Non-normal	$W(34) = .97$, $p = .39$	Normal
TBR central	$W(34) = .83$, $p < .001$	Non-normal	$W(34) = .96$, $p = .22$	Normal
TBR parietal	$W(34) = .83$, $p < .001$	Non-normal	$W(34) = .95$, $p = .10$	Normal

Note. Distributions that could not be transformed into a normal distribution are in bold. TBR= theta/beta ratio. RT= reaction time.

[a] log- normalization transformation

[b] test statistic and p value of Shapiro-Wilk test of normality

Hypothesis testing

Eyes aggregated

Correlations were calculated between TBRs (separately for each region) and the four behavioral measures (Stroop interference score[t], Stroop error percentage[t], no-go error percentage, common inhibitory control score), and tested for significance. Pearson correlations were calculated for normally distributed data, namely frontal and central TBR[t], and the four behavioral measures. Parietal TBR was non-normal even after log-normalization, so all correlations that were calculated with parietal TBR are Spearman correlations. Test statistics of all Pearson and Spearman correlations can be found in table 4 and 5, respectively. Bonferroni correction for multiple comparisons was applied to the test-wise critical α-levels to correct for the inflated experiment-wise type 1 error. None of the correlations were significant, even without Bonferroni correction.

Table 4

Test statistics of Pearson correlations between eyes aggregated TBRs and behavioral outcome measures

Measure	Frontal TBR[t]	Central TBR[t]
Stroop interference score[t]	$r(34) = -.05$, $p = .77$	$r(34) = -.07$, $p = .69$
Stroop error percentage[t]	$r(34) = -.04$, $p = .83$	$r(34) = -.02$, $p = .89$

No go error percentage	$r(34) = .02$, $p = .93$	$r(34) = .08$, $p = .64$
Common inhibitory control score	$r(34) = -.93$, $p = .60$	$r(34) = -.03$, $p = .88$

Note. TBR = theta/beta ratio.

Table 5

Test statistics of Spearman correlations between eyes collapsed parietal TBR and behavioral outcome measures

Measure	Parietal TBR
Stroop interference score	$r_s(34) = -.14$, $p = .43$
Stroop error percentage	$r_s(34) = .02$, $p = .93$
No go error percentage	$r_s(34) = -.01$, $p = .96$
Common inhibitory control score	$r_s(34) = -.04$, $p = .81$

Note. TBR = theta/beta ratio.

Eyes open

In the eyes open condition, Pearson correlations were calculated between TBR (separately per region) and the four behavioral measures (Stroop interference score[t], Stroop error percentage[t], nogo error percentage, common inhibitory control score) and tested for

significance. Table 6 displays the test statistics and p-values of the correlations. Bonferroni correction for multiple comparisons was applied to the test-wise critical α-levels to correct for the inflated experiment-wise type 1 error. None of the correlations were significant, even without Bonferroni correction.

Table 6

Test statistics of Pearson correlations between eyes open TBRs and behavioral measures

Measure	Frontal TBR^t	Central TBR^t	Parietal TBR^t
Stroop interference score^t	$r(34) = -.01$, $p = .95$	$r(34) = -.07$, $p = .68$	$r(34) = -.13$, $p = .47$
Stroop error perc.^{t}	$r(34) = .05$, $p = .76$	$r(34) = .15$, $p = .40$	$r(34) = .16$, $p = .37$
No go error perc.	$r(34) = -.14$, $p = .45$	$r(34) = -.05$, $p = .77$	$r(34) = -.03$, $p = .86$
Common inhibitory control score	$r(34) = .06$, $p = .73$	$r(34) = .13$, $p = .45$	$r(34) = .12$, $p = .48$

Note. TBR = theta/beta ratio. Perc = percentage.

Eyes closed

In the eyes closed condition, Pearson correlations were calculated between TBR (separately per region) and the four behavioral measures (Stroop interference score^t, Stroop error percentage^t, nogo error percentage, common inhibitory control score) and tested for significance. Table 7 displays the test statistics and p-values of the correlations. Bonferroni correction for multiple comparisons was applied to the test-wise critical α-levels to correct for the inflated experiment-wise type 1 error. None of the correlations were significant, even without Bonferroni correction.

Table 7

Test statistics of Pearson correlations between eyes closed TBRs and behavioral measures

Measure	Frontal TBR[t]	Central TBR[t]	Parietal TBR[t]
Stroop interference score[t]	$r(34) = -.01$, $p = .97$	$r(34) = -.00$, $p = .98$	$r(34) = -.01$, $p = .98$
Stroop error perc.[t]	$r(34) = .09$, $p = .60$	$r(34) = .12$, $p = .51$	$r(34) = .05$, $p = .79$
No go error perc.	$r(34) = -.05$, $p = .79$	$r(34) = -.02$, $p = .89$	$r(34) = -.03$, $p = .85$
Common inhibitory control score	$r(34) = .10$, $p = .56$	$r(34) = .14$, $p = .44$	$r(34) = .08$, $p = .64$

Note. TBR = theta/beta ratio. Perc = percentage.

Discussion

The aim of the current study was to investigate TBR as potential neural marker for inhibitory control in healthy young adults. It was hypothesized that TBR was negatively correlated with interference control (hypothesis 1), as well as response inhibition (hypothesis 2), which are the two subcomponents of inhibitory control. Interference control was measured by the Stroop task, more specifically the RT difference between congruent and incongruent conditions as well as the accuracy rate of the participants' responses. Response inhibition was measured by the go/ no-go task, namely the error rate of the no-go condition. Additionally, a common inhibitory control score was calculated out of all three outcome measures combined, which was hypothesized to be negatively correlated to TBR as well (hypothesis 3). These hypotheses were tested separately for 3 EEG conditions, namely eyes open, eyes closed, and - for comparability with previous research – eyes aggregated. Contrary to the expectations, the

current study found no relationship between TBR and inhibitory control in any EEG condition, neither for interference control (hypothesis 1) nor for response inhibition (hypothesis 2) or the common inhibitory control score (hypothesis 3). Thus, due to the lack of findings, the current study could not identify TBR as neural marker for inhibitory control skills in healthy young adults.

The idea that TBR might be a neural marker for interindividual differences in inhibitory control in healthy young adults emerged relatively recently. It stems from the great amount of evidence supporting the relationship between TBR and inhibitory control skills in the ADHD population and in developing children (Ahmadi et al., 2020; Arns et al., 2013; Barry et al., 2002; Bresnahan & Barry, 2002; Chabot et al., 2001; Huang et al., 2018; Zhang et al., 2019; Zhang et al., 2017). Due to the convincing evidence in other populations, Putman et al. (2010), Putman et al. (2014), Morillas-Romero et al. (2015), and Angelidis et al. (2016) investigated whether this relationship would also hold in the healthy population. Inhibitory control was assessed by the self-report measure ACS in all four papers, and Putman et al. (2010) and Morillas-Romero et al. (2015) additionally included a task as an objective measure of inhibitory control. Putman et al. (2010), Putman et al. (2014) and Angelidis et al. (2016) reported that TBR could predict interindividual differences in inhibitory control in healthy young adults. Morillas-Romero et al. (2015) however, did not find a relationship. The fact that three out of four papers yielded positive findings underlined the potential of TBR as neural marker of inhibitory control in the healthy population and the aim of the present study was to replicate these findings using tasks as objective assessment of inhibitory control. However, the current study, which did not find a relationship between TBR and inhibitory control in the healthy population, contradicts the limited but promising previous evidence and ais in line with the counterevidence. Consequently, the picture of TBR's potential to predict inhibitory control skills in the healthy population is now less clear. Thus, the current study has

contributed to a change of the overall impression of TBR as neural marker in healthy individuals.

Based on these results, there are two alternative implications. Either there is an actual relationship between TBR and inhibitory control in healthy adults, but the current research design failed to detect it. Or there is no relation in reality and the theory does not hold, irrespective of the research design. Regarding the former implication, the question arises why the current study might have failed to detect an effect. First, with 35 participants, the study's sample size was quite small. On the one hand, this number did not by any means satisfy the minimum number of 85 participants required to reach 80 % power, and the current study might have therefore had a low power. On the other hand, compared to other studies that have investigated the relation between TBR and inhibitory control and have found an effect, the sample size was on the lower side as well. Angelidis et al. (2016) and Putman et al. (2014) used 41 and 80 participants respectively, which might have given these studies more power to detect the effect. However, Putman et al. (2010) used only 28 participants, which suggests that a low sample size is not necessarily problematic. Contrarily, Morillas-Romero et al. (2015), who found no effect between TBR and inhibitory control in healthy adults, used a large sample of 110 individuals. This indicates that even studies with large sample sizes and high power might not be able to find an effect, so the small sample size of the current study might not be responsible for the negative findings. Because the investigation of TBR and inhibitory control in healthy adults is still in its infancy, there is a limited number of studies that the current study can be compared to. Although the previously discussed studies used a somewhat similar research design, the overall assessment methods differed quite strongly from the current study as mainly self-report measures were used to assess inhibitory control, which might lead to a lower comparability. Studies that investigated the relationship between TBR and inhibitory control using tasks to assess inhibitory control, only exist in the ADHD population. These highly comparable studies commonly used higher sample sizes than the

current study as well, for instance 62 (Orgim et al., 2011), 58 (Zhang et al., 2017), and 58 (Zhang et al., 2018), which further underlines that the present sample size is a low exception. Thus, the sample size of the present study is low, not only compared to the minimum required number of participants according to the 80 % power analysis but also compared to other studies from the healthy and ADHD population. This is a likely reason why no effect has been found and a higher sample size would without doubt have lent this study more power. However, some of the discussed studies have shown that an effect can also be detected with a low sample size and that a high sample size does not necessarily lead to the detection of an effect, pointing out the possibility that there might be a different problem concerning the research design or the theory.

The second potential reason why no effect has been found concerns the validity and reliability of the tasks and outcome measures. One measure-related reason for not finding an effect might be the psychometric properties of the Stroop task. Although the interference score has become a commonly used outcome measure of interference control, doubts have been raised about its validity. Paap et al. (2020) has investigated the concurrent and convergent validity of the interference score of the original Stroop task and concluded that the Stroop effect is not an appropriate measure of inhibitory control. This could account for the fact that no effect has been found in the current study. Additionally, the Stroop task and go/ no-go task used in the present study have been adapted from the original to be completed on the computer without being validated. It is therefore not exactly clear how valid these versions are, but a guess can be made by using validation studies of similar task versions. Penner et al. (2012) and Tyburski et al. (2021) have investigated the validity of such similar computerized versions of the Stroop and the go/ no-go task, respectively, and raised some doubts about the validity. Although the test-retest reliability of the computerized Stroop task was high, the performances on the computerized Stroop task and on the original version have not been found to correlate and the authors additionally described the nature of the adapted task as

changed compared to the original (Penner et al., 2012), which indicates poor convergent validity. Concerning the computerized go/ no-go task investigated by Tyburski et al. (2021), several test-retest measures were used. On the one hand, t-tests, Pearson correlations, and intraclass correlations (measuring the consistency between the scores of the two time-points) revealed that the no-go error rate during the first assessment did not differ from the second assessment and the performances of the two time points correlate. Hence, most test-retest measures indicated moderate test-retest reliability. On the other hand, however, reliable change indices which assess the probability of score differences between timepoints to fall within the probable measurement error range, indicated that there was no reliable change between timepoints for any participant. This indicates poor test-retest reliability. The inconsistent reliability findings of the computerized go/no-go task indicate that there might be some validity issues with its outcome measure. Overall, potential validity or reliability issues of the adapted tasks might be one of the measure-related reasons for the inability of the current study to find an effect. However, considering that there are several clinical studies that used the above discussed computerized task versions and found the expected effects (Assef et al., 2007; Belanger et al., 2010; Hepp et al., 1996; Moniz et al., 2016) it is unlikely that the lack of findings of the current study are solely due to validity issues of the adapted tasks. Yet, lower than optimal validity might have contributed to the combination of research design-related issues that together might be responsible for the failure of the current study to detect an effect. The last measure-related reason that could explain why no effect has been detected concerns the statistical analysis. Tasks that are used to measure psychological constructs like inhibitory control always measure task specific effects as well (such as colour processing or motor response speed), which are unrelated to the construct of interest. This is known as the task-impurity problem, formulated by Miyake and Friedman (2012). The authors suggest not to use the Stroop task alone to measure executive functions, as it might result in substantial measurement error. Instead, it is brought forward to use several tasks and estimate the

construct of interest with structural equation modelling. Structural equation modelling separately estimates the common variance (reflecting the construct of interest) and the unique variance (reflecting the error variance) for each task and combines it into one measure, resulting in greater measurement precision. In the current study, a common inhibitory score was calculated to account for the task-impurity problem, but it was done using z-scores as opposed to structural equation modelling, which does not reach the same measurement precision. Furthermore, two out of three outcome measures which were combined into a common inhibitory control score did not correlate with each other, which further introduces measurement error into the score. Additionally, the combination of not more than three outcome measures into a combined score limits the capability of the combined score to cancel out measurement error, as more variables more effectively cancel out task specific effects that are unrelated to inhibitory control. Thus, the manner of combining the outcome-measures into a common inhibitory control score was done in an error-prone way, which represents the last measurement-related potential reason why no effect has been found in the current study. An additional explanation for the lack of an effect could be insufficient spread of scores on the tasks and TBR, which will be touched upon later. Taken together, the discussed concerns regarding the current study's sample size, as well as validity of tasks and outcome measures might represent potential reasons why the research design might not have been able to detect an effect. However, this does not necessarily mean that the research design of the current study obscured an effect that is there in reality.

The alternative implication that follows from the current study's lack of finding is that there is indeed no effect in reality. In this case, the question arises why previous studies found an effect if the theory does not hold. The most pronounced difference between the previous studies and the current study is the way inhibitory control was measured. The current study used tasks to assess inhibitory control, which are despite the critique raised above objective measures of performance. Previous studies however, mainly used the self-report measure

'Attentional Control Scale', which might be less valid than tasks to assess inhibitory control skills due to the subjective nature of self-report measures (Stone et al., 2000). Validity issues of ACS are further supported by Williams et al. (2017) who reported that scores on ACS were unrelated to task performance of inhibitory control. It might therefore be the case that ACS measures a different construct than inhibitory control, which might have produced positive findings despite a lack of an actual effect. However, even a measure with poor construct validity is expected to produce consistent results, whether those are false positives (and therefore invalid) or not. This is not the case for studies using ACS to investigate the relationship between TBR and inhibitory control. Some of these studies yielded positive results (Angelidis et al., 2016; Putman et al., 2014; Putman et al., 2010) while a different study yielded negative results (Morillas-Romero et al., 2015). Hence, although construct validity issues of ACS might be likely a likely reason for potential false-positives of previous studies, the negative findings of Morillas-Romero et al. (2015) are not in line with this reasoning. A different explanation for the previous positive findings might be domain specificity of the results, which might not be generalizable to domain-general inhibitory control. While studies with an emotional design, either in the form of emotion induction (Putman et al., 2014) or an emotional go/ no-go task (Putman et al., 2010) were able to detect an effect, most studies using a neutral stimuli, as done by the present study and Morillas-Romero et al. (2015), found no effect. Taken together, this suggests that a relation might exist between TBR and emotion-related inhibitory control, but not for domain general inhibitory control, which might explain the previous positive findings. Especially the fact that the difference between emotional and neutral context also holds for papers that additionally included a task to objectively assess inhibitory control skills (Morillas-Romero et al., 2015; Putman et al., 2010), further increases the credibility of the results and the implication of domain-specificity. However, this does not account for the fact that Angelidis et al. (2016), who used a neutral context as well, did find a relation between TBR and inhibitory control.

All in all, it seems like there are potential reasons which might explain positive findings in case of absence of an actual effect. Nevertheless, neither validity issues of ACS nor domain-specificity of the effect could provide a full explanation of the positive findings, which is in line with all previous studies.

In case the second implication is true and there is indeed no actual effect, this means that TBR is not valid as neural marker for inhibitory control in healthy individuals. On the one hand, doubts about the appropriateness of TBR despite previous positive findings are not surprising because this research branch is in its infancy, and the hypotheses of the current study are based on limited evidence. New findings are therefore especially likely to refute previous evidence. On the other hand, doubts about the appropriateness of TBR in the healthy population are also somewhat surprising, considering the large scientific consensus about the measure's appropriateness in different populations, namely ADHD patients and children in a specific developmental stage. The question arises why TBR might serve as neural marker in some populations but not in others, especially because TBR is thought to reflect the interaction of the bottom-up and top-down attentional systems (Bishop, 2008; Katsuki & Constantinidis, 2014; Kim & Cave, 1999), which are thought to generally underly inhibitory control skills irrespective of the population. A reason for this distinction could be that there is insufficient variation in the healthy population, comparable to a ceiling effect, which might prevent TBR from discriminating individual differences of inhibitory control skills. Therefore, a clinical population might be necessary for an effect to be detected. However, by taking a closer look at the present study's data and comparing the variation of the Stroop interference score to the variation of ADHD patients on the same outcome measure, it is evident that the participants of the current study showed approximately as much variation on the interference score (King et al., 2007) and the no-go error rate (Dillo et al., 2010) as the ADHD group. The variance of TBR was also comparable to the variance of ADHD patients (Ogrim et al., 2011). Therefore, insufficient variance does not appear to be an appropriate

explanation for the inability of TBR to discriminate inhibitory control skills in healthy adults. Hence, while TBR appears to predict development-related differences in inhibitory control skills (as in ADHD and in developing children), it might not serve as a neural marker in the healthy population, that has gone through approximately the same normal development. It is not clear however what could explain these qualitatively different relationships of TBR and inhibitory control between populations.

The inconsistency of findings, that the current study has contributed to, shows that the role of TBR as a neural marker for inhibitory control in healthy individuals is less than clear. Yet there are some studies within the field of cognitive enhancement research which assume a relationship between TBR and inhibitory control in healthy adults and investigate whether TBR could be changed via Neurofeedback and whether these neural changes also translate into behavioral changes (Doppelmayr & Weber, 2011; van Son et al, 2020). The current findings are especially relevant to this field of research, as it might explain why all TBR Neurofeedback protocols have been found to be ineffective in healthy adults. Thus, although the current results did not reveal a relationship between TBR and inhibitory control skills in healthy adults, they might be useful to other research branches which might base studies on this assumed relationship.

Results of studies need to be interpreted in relation to the strength of their methodology. The main methodological strength of the current study was the objective measurement of inhibitory control by means of tasks after it had commonly been done with a self-report measure by previous studies. This provided a more valid assessment of the participants' skills. However, there are some limitations as well. First, the small sample size has probably limited to the power to find an effect. Second, the use of unvalidated adapted tasks has likely posed a threat to the validity of the outcome measures. Third, the small number of outcome measures used to calculate the common inhibitory control score and the use of z scores instead of structural equation modelling to combine the scores might have introduced measurement

error. Future research should counteract these problems by using a higher sample size to increase the power and validated tasks to avoid validity issues. Furthermore, a common inhibitory control score should be estimated using more outcome measures to cancel out task-specific effects more efficiently. These outcome measures should be combined into one score by structural equation modelling, to reach greater measurement precision. Moreover, the current study, which used frequentist statistics, only tested the probability of an effect (or H1), and not the probability of no effect (or H0) as it can be done with Bayesian statistic (Pek, 2020). However, based on the current findings, future research should specifically test the probability of the absence of an effect by using Bayesian statistics. The study of Gordon et al. (2018) can serve as an orientation as it has investigated the correlation between common RS-EEG measures (except TBR) and inhibitory control skills in healthy adults using Bayesian statistics. A replication of this study including TBR as an RS-EEG measure would further clarify the relationship between TBR and inhibitory control in healthy adults.

In conclusion, the current study did not find a relationship between TBR and inhibitory control skills in healthy individuals, contrary to the expectations. In relation to the previous mostly positive findings, the present results are in line with the counterevidence, which decreases the initial confidence in the potential of the measure. However, the findings do not necessarily mean that such a relation does not exist as the lack of evidence could be due to methodological limitations. Therefore, future research should be conducted to clarify the potential of TBR as neural marker for inhibitory control skills in healthy adults.

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