Revisiting the Neurocognitive Correlates of the Behavioral Inhibition and Activation Systems

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Cover Letter

Along with this letter, we present to you the Registered Report for our planned replication of the 2008 paper by Amodio et al., titled 'Neurocognitive components of the behavioral inhibition and activation systems: Implications for theories of self-regulation'. This replication is part of the #EEGManyLabs project, an international community driven initiative that identified some of the most frequently cited but insufficiently replicated EEG studies (Pavlov et al., 2021, Cortex). If accepted for publication, this paper would, following an agreement with Chris Chambers, form part of a special collection of articles in Cortex on this seminal project.

The Amodio et al. (2008) paper is a worthy candidate for replication for two reasons: Firstly, the paper is cited frequently, with 599 citations according to Google Scholar at the time of writing. Yet, despite its impact on the field, there are no direct replications of the study, and its original sample size of 40 participants is not adequate to guarantee robust results.

Second, the topic investigated in this paper – neurocognitive correlates of the BIS and BAS systems, investigated through correlations with the Carver and White BIS/BAS questionnaire – is a topic of continuous discussion. The exact nature of these constructs remains ambiguous due to a large body of literature with largely conflicting results. A replication study of one of the most frequently cited works from this field, using a larger sample size that generates enough statistical power to find even small effects, will solidify the currently wavering judgment on whether the neurobiological markers measured here are reliable reflections of BIS and BAS.

All necessary support for the study is secured. All replicating labs have both the facilities, the equipment, and the staff to collect the required data with high standards of accuracy.
At this time, not all replicating labs have obtained approval by their respective local ethics committees yet. However, each of the labs operates under Standard Operating Guidelines, the use of which was approved in previous ethics judgments. Renewed ethical approval for this study will be sought before data collection.

The replicating labs agree to share their raw data, the full list of digital material including questionnaires, and the code for stimulus presentation as well as analysis, as detailed in the #EEGManyLabs position paper (Pavlov et al., 2021).
Following Stage 1 in principle acceptance, we will register the approved protocol on the Open Science Framework (as a component in #EEGManyLabs OSF page; https://osf.io/yb3pq/), under private embargo until submission of the Stage 2 manuscript. As soon as appropriate, the data, material, and code will also be made openly available there.

Overall, the study is expected to take up to 11 months (or one year including possible delays) between acceptance of the Stage 1 report and submission of the Stage 2 Report. If currently unforeseeable events will happen that hinder the process of the study, the paper must later be withdrawn. In this case, we agree to publish a short summary of the pre-registered study in Cortex, under the section Withdrawn Registrations.

Abstract

The Behavioral Inhibition System (BIS) and the Behavioral Activation System (BAS) are cornerstones of neurobehavioral research. Personality scales have been developed to capture the behavioral and motivational tendencies associated with these systems, and many studies have attempted to link these scales with basic neurocognitive processes. The results, however, have been inconclusive. Here, we aim to replicate a seminal study on this topic by Amodio et al. (2008), in which the authors used a Go/No-Go task to test the association of the trait BIS with cognitive control and the BAS trait with approach tendency. The authors found significant correlations that were mutually exclusive from each other; BAS did not correlate with measures of cognitive control, and BIS did not correlated with measures of approach tendency. Despite the paper's high citation frequency and influence on the field, there has been no direct replication to date. These factors motivated the inclusion of this study in the #EEGManyLabs project, an international community-driven effort to replicate influential EEG results and this registered report forms a part of this initiative. Following the original study, a Go/No-Go experiment will be performed with a total of 320 participants across eight replicating labs. EEG will be recorded both during the experiment and in an eight-minute resting period. Target variables are the amplitude of the N2 during a successfully inhibited response, the amplitude of the error-related negativity (ERN) after an erroneous response, left frontal asymmetry (LFA) during rest, and trait BIS/BAS measured by the Carver and White questionnaire. Both Pearson's and Spearman rank sum correlations, as well as regression analyses will be used to test the hypotheses that trait BIS is associated with ERN and N2 amplitudes, and that trait BAS is associated with LFA during rest.

Introduction

Research on non-human animal neurobehavioral systems has led to the development of the idea that there are two principally separate systems that govern behavioral regulation: The Behavioral Inhibition System (BIS) and the Behavioral Activation System (BAS). In this concept, the BAS is a collection of cognitive systems that regulate approach towards a stimulus and activated by either a potential reward or the need to avoid punishment. Conversely, the BIS interrupts both approach and avoidance, while increasing attention and arousal, and is activated by conflicting stimuli (Gray & McNaughton, 1982). 'Inhibition' in the context of the BIS is not to be confused with the term 'inhibition' used in cognitive sciences more broadly, where it usually refers to actively halting or suppressing an action. Instead, the inhibition of BIS refers to an automatic attentional reaction to a conflicting stimulus, which interrupts ongoing behavior to engage with the new stimulus.

To support the measurement of these core behavioral systems, *trait* BIS/BAS was developed as a personality dimension or motivational tendency. The most commonly used tool to capture trait BIS and BAS is a 20-item questionnaire by Carver and White (1994), with 7 BIS items and 13 BAS items. Trait BAS captures approach tendencies and trait BIS has been conceptualized as a number of partially conflicting concepts, including most notably behavioral inhibition or behavioral avoidance (Amodio, Master, Yee, & Taylor, 2008), but also sensitivity to punishment (Boksem, Tops, Kostermans, & De Cremer, 2008), and more specifically, anxiety in response to cognitive

conflict (Weydmann, Hauck Filho, & Bizarro, 2020).

One of the central endeavors of psychophysiological research is finding neurobiological processes that form the basis of sustained differences in behavior and personality (Amodio et al., 2008). It is therefore imperative to find reliable neurological correlates of personality traits such as trait BIS and BAS.

Trait BAS, the motivational tendency for approach/ avoidance, has often been found to be connected to asymmetrical frontal activity, as measured by the decrease of alpha power at frontal electrodes. Increased left frontal activity relative to right frontal activity, called left frontal asymmetry (LFA), during rest was connected to greater approach tendency and increased relative right frontal activity to avoidance or withdrawal tendency, irrespective of the emotional valence (Harmon-Jones, 2003a; Harmon- Jones, 2003b). In line with these findings, trait BAS was frequently found to correlate with LFA (Coan, Allen, & McKnight, 2006; Sutton & Davidson, 1997).

For trait BIS, one potential neural correlate is the ERP component N2, a negative deflection in the EEG signal that can be measured at fronto-central electrodes between 200 and 300 ms after a relevant stimulus (Donkers & Van Boxtel, 2004). In the context of a Go/No-Go Design that would be a No-Go Stimulus – the rarer stimulus, that requires inhibition of the habitual response (Bruin, Wijers, & Van Staveren, 2001; Donkers & Van Boxtel, 2004; Nieuwenhuis, Yeung, Van Den Wildenberg, & Ridderinkhof, 2003). Because of this, the N2 was believed to reflect inhibition of action. However, there is evidence that it reflects cognitive conflict and conflict detection instead, arising from the conflict between the habitual response to the more frequent stimulus (Go) and the different response required by the rare stimulus (No-Go) (Donkers & Van Boxtel, 2004). This role in conflict detection is backed by results from clinical samples; for example, patients with obsessive compulsive disorder had larger N2 amplitudes than healthy controls (Riesel, Klawohn, Kathmann, & Endrass, 2017). However, the exact functional role of the N2 is a matter of continued debate, with plentiful support for both the interpretation as reflecting response inhibition (Hoyniak & Petersen, 2019) and conflict detection (Larson, Clayson, & Clawson, 2014). Some newer studies even argue that neither capture the core of the N2 (Mussini et al., 2020), though the involvement in both processes is undeniable.
The N2 is thought to be generated in the anterior cingulate cortex (Righi, Mecacci, & Viggiano, 2009; Van Veen & Carter, 2002). Other neural generators have been found, and a reduction to one dipole generator is likely to be an unjustified simplification of cognition in the human brain. However, the ACC is the area that is reported consistently (Bekker, Kenemans, & Verbaten, 2005).

The second notable neural correlate of trait BIS is the error-related negativity (ERN), a fronto-central negative deflection roughly 100ms after the execution of an incorrect response during forced-choice reaction time tasks (Gehring, Goss, Coles, Meyer, & Donchin, 1993). The ACC is also a likely neural generator of the ERN (Miltner et al., 2003), where a reduction in dopaminergic activity can be observed following errors (Holroyd & Coles, 2002).

The functional relevance of the ERN has been discussed at length in the literature. The generally

accepted view is that the ERN signifies a mismatch between the correct response and the actual response (Coles, Scheffers, & Holroyd, 2001; Falkenstein, Hoormann, Christ, & Hohnsbein, 2000; Gehring et al., 1993; Scheffers & Coles, 2000; Scheffers, Coles, Bernstein, Gehring, & Donchin, 1996). This can turn the ERN into an important tool for observing the cognitive processes of error monitoring and conflict detection.

Replicated study

Here we aim to replicate a study by Amodio, Master, Yee, and Taylor (2008), one of the most influential EEG studies of the past 20 years. It established a critical empirical basis for the argument that BIS/BAS measure two different cognitive systems, cognitive control and avoidance tendency, respectively. This importance, combined with the study's small sample of 40 undergrad students and, as far as we can discern, a lack of direct replications calls for a coordinated replication effort.

The present study is also part of a larger international project called #EEGManyLabs (Pavlov et al., 2021). The aim of the project is the replication of multiple influential EEG studies which, to this date, have either not been replicated at all or have had an inconsistent history of replicability. The selection of studies for replication involved a multi-stage process. Initially, studies were chosen based on their frequency of citation. Following this, members of the #EEGManyLabs network further refined the selection by voting for the studies they deemed most influential and worthy of replication, which can be argued to reflect the influence of a given study. Within this project, a replication of a different study by Amodio and colleagues (Amodio, Jost, Master, & Yee, 2007) is also being undertaken. These two original studies have near identical experimental designs, both employing a Go/No-Go design with matching stimuli and timing. The differences pertain to the additional questionnaires and a resting state recording before the experiment. Where the 2008 study assessed trait BIS and BAS, the 2007 study reported a single-item measure of political conservatism vs. liberalism. These questionnaires will be combined so that both replications can be conducted with the same dataset, allowing for two replications with comparatively low resource requirements. Analyses and discussions on these distinct topics will be kept separate in the respective reports.

The original study aimed to differentiate the BIS and the BAS traits on a neurocognitive level, which could inform theoretical discourse whether they are aspects of the same system or two separate systems. BIS and BAS were measured with a self-report questionnaire (Carver & White, 1994), resting state EEG was measured, and a Go/No-Go task was performed by the participants. The core results were as follows: Trait BIS correlated negatively with No-Go N2 amplitudes (r = -.41, p<.05) and with incorrect No-Go ERN amplitudes (r = -.35, p < .05). Please note that in this study, for the sake of simplicity and consistency with other literature, these correlations will be considered in reverse. The ERN and N2 are negative components, meaning a that larger amplitude, indicative of higher related activity, can be represented by a more negative number. In that logic, a larger N2 amplitude that goes along with higher BIS results in a negative correlation. We will instead speak about absolute amplitudes, in which case the original correlations would be positive.

Resting-state LFA, measured by decreased relative left frontal alpha, was positively associated with BAS (r = .36, p < .05), but not with BIS; A single dipole model of the N2 peak placed the dipole in the ACC (R^2 = 91.4%). Additionally, two regression analyses were calculated as confirmation of the prior results: A regression of BIS on the predictors LFA, BAS, and No-Go N2 amplitude returned a significant effect only for the N2 amplitudes (β = -.47, t(36) = 3.04, p<.05); And a regression of BAS on the predictors BIS, No-Go N2, and LFA returned a significant effect only for frontal asymmetry (β = .42, t(36) = 2.65, p < .02).

Amodio and colleagues interpreted their results as having shown that trait BIS indeed reflects inhibition tendencies rather than avoidance tendencies (Amodio et al., 2008). They argued that inhibiting an ongoing action to engage with a new stimulus is analogous to the detection of cognitive conflict as it happens during No-Go trials. Therefore, the N2 amplitude during No-Go trials can be used as an indicator for behavioral inhibition. On the other hand, LFA was used as an indicator for approach/ avoidance tendencies. Since trait BIS was found to be correlated with the N2 amplitudes but not frontal asymmetry, it reflects inhibition and not avoidance. And since trait BAS was found to be correlated with frontal asymmetry, but not the N2 amplitudes, it reflects approach tendencies. This double dissociation was considered the main contribution of the study to ongoing discourse, which to that point had not clearly placed BIS as either inhibition or avoidance.

Current research after the original study

As stated above, there are no direct replications of the study by Amodio et al. (2008). There are, on the other hand, many studies that have investigated closely related questions.

Regarding the N2 amplitude, there have been some studies with a similar experimental setup. Leue et al. (2012) varied the reinforcement during the Go/No-Go task and found a significant correlation between No-Go N2 and trait BIS only for the aversive verbal- and monetary reinforcement category. Regardless, the association was generally in line with Amodio et al. (2008). Scheuble et al. (2019), on the other hand, used a new motivational framing, which inverted the results found by Amodio et al. In this study, the No-Go N2 correlated with trait BAS, but not with trait BIS. In an Erikson Flanker task (a related task requiring cognitive control), Boksem et al. did not find any correlation between N2 and trait BIS (Boksem, Tops, Wester, Meijman, & Lorist, 2006). There are also several publications that tested for a link between trait anxiety and the N2 amplitude. As mentioned above, trait BIS is sometimes conceptualized as an aspect of anxiety or as a closely related construct. Some studies found that N2 amplitudes were increased with increasing trait anxiety (Righi et al., 2009; Sehlmeyer et al., 2010), while others have found the reverse connection of lower amplitudes for high-anxiety individuals (Xia, Mo, Wang, Zhang, & Zhang, 2020; Zhu et al., 2009). A 2015 meta-analysis reported a small positive correlation, but with considerable variation in the results (Cavanagh & Shackman, 2015).

The case of the ERN is similarly ambiguous. In two studies employing a Flanker task trait BIS was found to correlate with the ERN amplitude (Boksem et al., 2006; Tops & Boksem, 2011). Another study reported the same results – but only in an experimental condition that involved punishment in the form of subtracting monetary reward for each mistake, not in another condition

that instead used omission of rewards (Boksem et al., 2008). In a study by Pasion et al. (2018), the association of ERN and BIS only approached significance in a condition of sustained threat and not under other conditions. Just as in the case of the N2, there is also a study that reported results which point in the opposite direction from those reported by Amodio et al. (2008): In a spatial Stroop task, the ERN amplitude was negatively correlated with trait BAS, and not significantly correlated with trait BIS (Maruo, Schacht, Sommer, & Masaki, 2016).

Moving on to frontal asymmetry, trait BAS was found to be connected to LFA, but this link is far from consistent (Kaack, Chae, Shadli, & Hillman, 2020) with some studies reporting it, while others did not (Kaack et al., 2020). Meta-analytic evidence also speaks against a reliable association of LFA and trait BAS, despite frequent assumptions to the contrary (Kuper, Käckenmester, & Wacker, 2019; Wacker, Chavanon, & Stemmler, 2010). This inconsistency might be due to varying experimental conditions, as not all resting state recordings have the same framing. For example, Kuper et al. (2019) argued that the association between BAS and resting frontal asymmetry might only exist within an overall approach-motivated context. Additionally, not all studies used the same questionnaires to measure BAS.

In summary, for both trait BIS and trait BAS, neurobiological bases are often assumed and investigated, but the associated correlations are inconsistent in the literature, which might be in part due to variations in methodology. For the theoretical implications of the original study to be upheld, a reliable replication should try to confirm the individual effects and their double dissociation.

Aim and Hypotheses

The present study aims to perform a direct replication of Amodio et al.'s (2008) original study. We will follow the original paper's data collection, preprocessing, and analysis procedures as closely as possible. The study will be based in multiple replicating labs from different countries contributing to the data collection. Beyond a substantially powered analysis of pooled data collected across all labs, we will also conduct an internal meta-analysis across the findings from each individual lab. The study material, including analysis pipelines and code, will be made openly available.

Our hypotheses, based on Amodio et al. (2008) and recent literature, are as follows:

1a) Trait BIS is positively associated with the absolute N2 amplitude during correct No-Go trials

1b) Trait BIS is positively associated with the absolute ERN amplitude during incorrect No-Go trials

2) Trait BAS is positively associated with resting state LFA

3) The aforementioned associations are mutually exclusive (double dissociation); That is, trait BIS is not associated with resting state LFA, and trait BAS is not associated with either N2 or ERN amplitudes.

Since the study of Amodio and colleagues remains a pillar of empirical support for these hypotheses, this replication will add much needed certainty, establishing whether these neurobiological markers of cognitive activity are reliable reflections of trait BIS and BAS, and

whether these systems can be separated based on mutually exclusive neural correlates.

Methods

The experiment will follow the design reported by Amodio and colleagues. Participants will be informed about the experimental procedure and their rights as participants according to ethical guidelines. After signing their informed consent, they will be seated comfortably in a dimly lit room.

Questionnaires

An online questionnaire will be used to assess several relevant groups of information. This will take place before the EEG experiment. There will be standard questions regarding the use of psychoactive substances within 24 hours before the experiment, and the handedness of the participants (Edinburgh Handedness Inventory, Oldfield, 1971).

To assess trait BIS/BAS as a direct replication, we will utilize the Carver and White questionnaire (1994), which consists of 7 BIS and 13 BAS items. Average scores will be calculated separately for both scales. However, using only the Carver and White scale offers a somewhat limited view on the construct we are interested in. Despite its frequent use, the scale may not be optimal for measuring trait BIS/BAS by itself, which is why some studies have taken to measuring multiple related scales (see Kaack et al., 2020). We therefore plan to additionally use the Sensitivity to Punishment and Sensitivity to Reward Questionnaire (Torrubia, Ávila, Moltó, & Caseras, 2001), where the operationalization of trait BIS and BAS is based on the conceptualization of high and low anxiety and impulsivity. It comprises of 48 items, 24 per scale, that posit yes-or-no questions the participants are asked to answer. The additional use of this measure will increase the reliability and validity of trait BIS/BAS and, thus, will go beyond the original replication study by increasing measurement accuracy.

In addition to this, there will be questionnaires regarding matters unrelated to this study. This is because, as mentioned previously, this study is one half of a joint replication of two papers, details of which will be presented in a separate Registered Report. The additional questionnaires include 70 items in total and pertain to political orientation and other personal beliefs and convictions.

All labs that recruit other than English speaking participants will use translated versions of these questionnaires, validated for the differing cultural context. If not available, we will apply the translation procedure developed by Psychological Science Accelerator (Moshontz et al., 2018) that involves forward and back translation by native speakers followed by cultural adjustments (this process has been used successfully in several multi-national studies already, see https://psysciacc.org/how-we-work/ for detail). Additionally, we will report the psychometric reliability metrics for each questionnaire.

Experimental task

Resting state EEG will be recorded in eight 1-minute intervals, alternating between eyes open and eyes closed. The order (beginning with open or closed eyes) will be counterbalanced across participants. After each eyes-closed interval, participants will be notified to open their eyes again through an intercom or an automatic sound via loudspeaker.

The experimental task will be displayed using PsychoPy (Peirce et al., 2019) and represents a classic Go/No-Go paradigm. It consists of 500 trials, with 80% presenting the Go stimulus and 20% the No–Go stimulus. Participants will have a two-minute break halfway through the task. Before the experiment, participants will complete a practice session with 40 trials, 50% of which are Go-trials, to familiarize them with the design and give the option to ask clarifying questions.

On each trial of the Go/No-Go task, either the letter “M” or “W” will be presented in green in the center of an otherwise black screen. One of these letters will serve as the Go Stimulus, and participants will be instructed to press the right shift key on a computer keyboard on the desk in front of them as quickly as possible when they see the letter. The other letter will serve as the No-Go stimulus, and participants will be instructed to withhold any response when they see the letter. The high frequency of Go stimuli will induce a habitual “Go” response, leading to a difficulty of successfully inhibiting a response on No-Go trials. The assignment of either “M” or “W” as Go or No-Go Stimulus will be counterbalances across participants, based on subject ID, wherein even-numbered IDs will have “M” as the Go stimulus and odd-numbered IDs will have “W” as the Go stimulus.

Each trial will begin with a fixation point, presented for 500ms. The target then appears for 100ms, followed by a black screen, displayed for a maximum of 900ms or until a response occurs. Participants can respond during the entire 900ms, and all responses will be considered valid, but they will be instructed to respond within 500ms of target onset. A red “Too slow!” warning message will appear after responses that exceed this time limit or if no response is given 1000ms after stimulus onset, and a red “Incorrect” feedback will be given after erroneous responses to the No-Go stimulus. Each feedback will be displayed for 1s. No feedback is given for correct responses (i.e. a timely response in Go-trials or an omission of response in No-Go trials). The text will be translated for replicating labs in non-English speaking countries. See Figure 1 for a visualization of the trial structure. The entire task will take about 20 minutes.

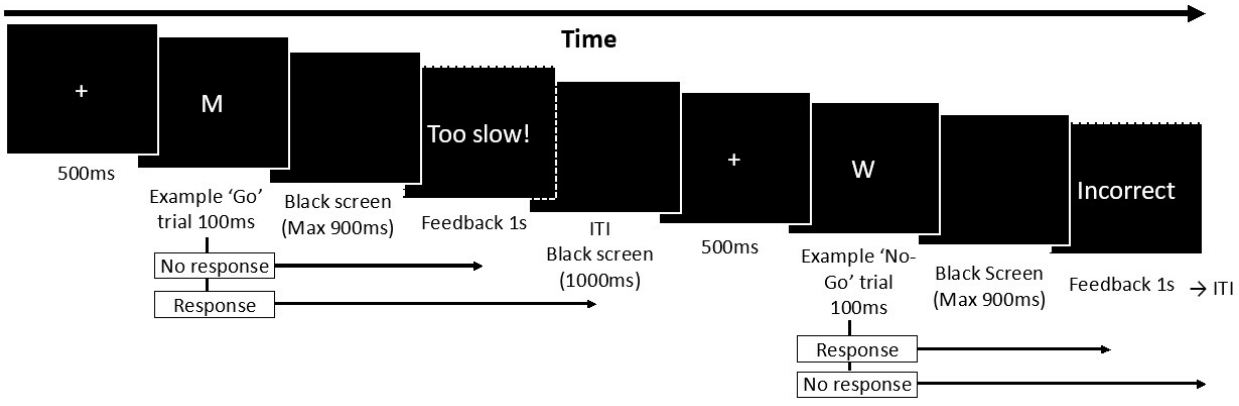

Figure 1: Trial structure of the Go/No-Go experiment. The Feedback will be translated to each replicating lab’s respective language.

EEG Recording

Participants will be fitted with an EEG cap, with Ag/AgCl electrodes arranged according to the (extended) 10-20 system. An electrode on the left earlobe will serve as the active reference, and a second electrode on the right earlobe will be used to re-reference to average earlobe offline, as per the original study's protocol. A ground electrode will be placed in varying positions, depending on the lab. If available, vertical and horizontal electrooculogram (EOG) will be recorded to allow for the accurate removal of eye-movement artifacts. If necessary for the respective EEG system, conductive gel will be used to improve the contact between electrodes and the scalp. Impedances will be lowered to a threshold appropriate for the given system (under some conditions deviating from the original threshold of 5 kΩ; see Table 1). EEG will be recorded without online filters and digitized at a minimum of 500 Hz. The specific setup of the individual replicating labs can deviate slightly from this general plan – the number of electrodes is variable and can range from 28 to 64. Regardless of that, however, the relevant electrodes Cz, FCz, F3, and F4 will almost always be included and always be at the same scalp position (with the exception of the FCz, as some EEG equipment lacks an electrode at the FCz position. Those labs will use the Cz as a substitute, which has been shown to be capable of capturing the ERN as well (Yasuda, Sato, Miyawaki, Kumano, & Kuboki, 2004). The brand and type of the equipment (caps, gel, amplifier) will also vary between labs. See Table 1 for an overview of the systems used in each currently registered replicating lab. All labs will use PsychoPy for stimulus presentation and MATLAB, EEGLAB and R for analysis, but data recording software may vary.

Table 1: List of EEG systems and electrode setups for each replicating lab

University	Location	Amplifier	EEG System	Sampling Rate (Hz)	Electrodes + External electrodes	Default reference + Ground	Conductive Gel	Active/ Passive Electrodes +(kΩ max)	Online filter (Hz)	EOG (Y/N)	Operating System
Sunway University	Malaysia	CGX	CGX Quick-32r (Dry system)	500	32	Left earlobe	None	Active (25)	0.1 - 40	N	Windows 10
University of Bremen	Germany	REFA, TMSi	EASECAP	512	64 + 3	Left earlobe + cheek	Abralyt HiCl	Passive (5)	NA	Y	Windows 7
University of Alabama	USA	Brain Vision actiCHamp Plus	Brain Vision actiCAP Snap	512	64 + 2	Right earlobe + FPz	EasyCap SuperVisc High Viscosity Electrolyte-Gel	Active (25)	NA	N	Windows 10
Hamilton College	USA	Biosemi ActiveTwo	Biosemi ActiveTwo	512	64 + 8	CMS (Common Mode Sense)	SignaGel	Active (25)	NA	Y	Windows 7
ISCTE-Instituto Universitário de Lisboa	Portugal	actiCHAMP amplifier	actiCAP slim, Brain Vision	500/1000	32 + 5	Fpz + FCz	SuperVisc High Viscosity Electrolyte-Gel	Active (10)	NA	Y	Windows 7
University of Toronto	Canada	Advanced Neuro Technology (ANT) TMSi Refa8	ANT	512	32 + 4	Left & right earlobe	Electro-Gel	Passive (5)	NA	Y	Windows 8
MSB Medical	Germany	Brain Products	Brain Products	1000	32 + 2	FCz + Fpz	EasyCap	Active	NA	N	Windows 10

School Berlin		(brainAmp) System				(left earlobe + Fpz alternatively)	SuperVisc High Viscosity Electrolyte-Gel	(25)			
George Mason University	USA	Brain Products BrainAmp	Brain Products actiCAP slim	500	32	FCz + Fpz	Easy Cap SuperVisc High Viscosity Electrolyte-Gel	Active (25)	0.1 - 250	N	Windows 10

Known differences from the original study:

While our goal is to perform a direct replication of the original study, there are some notable deviations and additions, which are reported here for completeness. In a deviation from the original protocol we will record the EEG without online filters and digitize it at 500 Hz or more, depending on the lab, instead of 1000 Hz. The first [0.1 - 100] Hz filter that Amodio et al. applied online will instead be added offline during preprocessing. The frequencies analyzed in this study will be unaffected by the change of sampling rate. As Table 1 shows, not all labs are equipped to replicate the original earlobe referencing and the EOG recording. In the latter case, frontopolar electrodes will be used to identify ocular artifacts.

The questionnaires will be administered before the EEG setup, whereas in the original study they took place between resting state recording and the task. In addition to the Carver and White BIS/BAS scales recorded in the original study, we will include additional questionnaires to increase the validity of the personality measurements (see above for the full list). The correlations and regressions for the Hypothesis tests will be calculated once with the original questionnaire and once with the newly added Sensitivity to Punishment and Sensitivity to Reward Questionnaire.

A secondary EEG analysis will be performed, using modern and standardized preprocessing methods. The results of this analysis will be compared with the ones according to the replicated original methods.

Sample size & inclusion criteria

For power analysis, we used half of the effect sizes found in the original paper, to correct for effect size overestimation through publication bias. The smallest reported effect size was the correlation between the ERN amplitude and trait BIS (r = .37). Additionally, we set the power to 90% and level of significance to p < .02.

Calculating the optimal sample size with GPower (Erdfelder et al., 1996) for a bivariate Pearson's correlation with these parameters returns a sample of N = 320. To make sure that we reach that amount, each of the 8 replicating labs will provide an average of 45 participants, resulting in a collective sample size of 360 and ensuring an adequate sample even after exclusion.

Participants will be recruited via online recruitment systems, advertisements, and/or specialized mailing lists, depending on the local circumstances of each replicating lab. As per common EEG inclusion criteria, participants must have normal or corrected to normal vision, be right-handed, and speak the native language of the lab's respective country fluently. Since the original study included only undergraduate students, we will limit our sample to undergraduate students too. There is no limitation regarding their subject of study.

Exclusion criteria

The original study specified 3 exclusion criteria: (1) Participants will be excluded in case of heavy pollution of the data through artifacts; (2) failure to follow task instructions; or (3) scores on one or more scales being in outlier range (difference to the mean of >3 standard deviations, SD).

The current study will follow the same criteria. The first rule is specified as follows: Participants will be excluded if, due to artifact pollution or task performance, fewer than 8 incorrect No-Go trials remain for extraction of the ERN or fewer than 20 correct No-Go trials remain for extraction of the N2. This threshold was chosen because the ERPs are not accurate for fewer trials (Olvet & Hajcak, 2009; Rietdijk, Franken, & Thurik, 2014). Regarding the second rule, participants will be considered to have failed task instructions if their total number of correct trials is more than 3 SD lower than the average.

Additionally, a fourth exclusion criteria will be set as follows: If a dataset is heavily corrupted with noise in any of the electrode channels central to this analysis, the participant will have to be rejected. The channels in question are: Cz, FCz, F3, F4, and VEOG/ Fp1+Fp2 (for the regression of blink artifacts, see below).

Confirmatory analysis plan:

EEG Analysis

The confirmatory analysis will follow the process laid out in the original study by Amodio et al. (2008). There will be two separate EEG preprocessing and analysis pipelines, one for the analysis of frontal asymmetry and one for the ERP analyses. These steps will be performed in MATLAB using EEGLAB (see Software and Code Availability for details).

For the analysis of frontal asymmetry, the recorded resting state EEG will be used. A 0.1 – 100 Hz bandpass filter will be applied. Blink artifacts will be rejected using an automatic algorithm, removing all EOG deflections of 75μV or larger. Artifacts associated with movement will be removed manually. Epochs with a length of 2048 ms will be extracted using a Hamming window from artifact free sections of the resting EEG. That is, a Hamming kernel of length 2048 ms will be created using hamming.m, and multiplied by each of the data epochs separately. If possible, epochs will be overlapped by 75% to minimize loss of data due to Hamming window extraction. The discrete Fourier transform of each extracted epoch will be computed using fft.m, after which power is computed as the magnitude squared (i.e., abs(fft(x)).^2). Next, power will be averaged over all epochs from each of the resting trials individually. From the averaged power spectra, only the alpha band (8-13 Hz) will be extracted. Amodio et al. (2008) considered activity in this spectral range to be inversely related to cortical activity. The power values will be transformed with a natural logarithm using log.m and then averaged over all 8 1-min resting conditions (i.e., 4 eyes open and 4 eyes closed). Alpha asymmetry will be calculated as right frontal log-alpha power, measured at the electrode site F4, minus left frontal log-alpha power, measured at the electrode site F3. Therefore, higher scores indicate greater right-sided alpha, and, inversely, greater left-sided cortical activity.

For the ERP analysis, the data recorded during the trials of the Go/No-Go experiment will be used. A 0.1 – 100 Hz bandpass filter will be applied. Blink artifacts will be corrected using a regression-based automatic algorithm. The algorithm will use the signal from the VEOG channel as basis for the regression, or an average of Fp1 and Fp2 if there is no VEOG channel in the respective lab's setup. Trials with muscle artifacts will be removed manually. Additionally, trials

that contain response times under 200ms will be removed, as it is unlikely to be a volitional response to the stimulus. This limit was chosen after correspondence with David Amodio who informed us about an identical procedure in the original study. A 1 to 15 Hz bandpass filter will be applied to the data (48 dB, zero phase shift).

For the N2, 1000ms stimulus-locked epochs will be extracted for each artifact-free trial, beginning 200ms prior to stimulus onset and ending 300ms after the latest possible response. A baseline correction will be applied, subtracting the average pre-stimulus voltage from the entire epoch. Averaged epochs will be calculated separately for trial type (Go/No-Go) and response (correct/ incorrect). The No-Go N2 component will be scored as the peak negative deflection (local peak) between 200 and 400ms after target onset at electrode Cz, specifically for No-Go' trials with correct (successfully withheld) responses. The average amplitude of the No-Go N2 will be extracted for each participant.

For the ERN, 800ms response-locked epochs will be extracted for each artifact-free trial, beginning 400ms before the response and ending 400ms after response. A baseline correction will be applied, subtracting the average pre-response voltage (-150 to -50 ms) from the entire epoch. As for the N2, epochs will be averaged separately for trial type (Go/No-Go) and response (correct/ incorrect). The ERN will be scored as the peak negative deflection (local peak) occurring between -50 and 150ms at electrode FCz, specifically for No-Go trials with incorrect responses. The average amplitude of the ERN will be extracted for each participant.

To increase the results' validity and replicability, a secondary processing pipeline will be set up that includes updated and standardized preprocessing methods. The results obtained with the data processed in this manner will be compared to the results obtained from the data processed with the original methods. The updated processing pipeline includes (a) applying a notch filter of 50Hz to remove noise caused by the electrical power grid (for US-based labs, it will be 60 Hz instead), (b) applying a bandpass filter of 0.1-30 Hz (e.g., Härpfer et al. 2020), (c) conducting spherical interpolation of the channels with invariant activity or activity that deviates significantly from other channels based on visual inspection of data, (d) removal of extremely noisy data segments (for improving ICA performance) as detected by EEGLAB's clean_artifacts.m function, which uses the artifact subspace reconstruction (ASR) algorithm, (e) cleaning the data of ocular, muscular, or 'bad' channel artifacts with Independent Component Analysis (using the function 'runica' implemented in EEGLAB), and (f) rejecting bad epochs, namely those deviating more than 3.29 SD (Tabachnick, Fidell, & Ullman, 2013) from trimmed normalized means with respect to joint probability, kurtosis or the spectrum. For this rejection, only the channels relevant for the following analyses will be considered, to avoid rejecting episodes unnecessarily. The same epoching and baseline correction measures will be applied here as in the original pipeline.

To standardize our selection of artifacts as much as possible, we will use the SASICA (Semi-Automated Selection of Independent Components of the electroencephalogram for Artifact correction) plugin in EEGLAB (Chaumon, Bishop, & Busch, 2015). The following options will be enabled in SASICA: 'Autocorrelation' to differentiate muscle components (components reflecting brain data are known to be strongly autocorrelated), 'Focal components' (to determine bad

channels), ‘Focal trial activity’ (to check for rare events, specifically artifacts with unusually large amplitudes), ‘Signal to noise ratio’ (to reject components with a low signal to noise ratio), and ADJUST (for detection of eyeblinks, and vertical and horizontal eye movements). The final decision to reject or retain components will be based on SASICA’s recommendations, as well as visual inspection of each component’s topography and overall component data (using EEGLAB’s data scrolling feature). In ambiguous cases, we will also employ the use of ICLabel and reject components based on their probability of being a brain component (rejection if the probability is below 30%). The other data exclusion criteria will be carried over from the old pipeline. Lastly, in order to improve the robustness of ERP results, the updated processing will not simply use the peak amplitude. Instead, the peak amplitude in the relevant time frame of the given ERP will be identified and the mean amplitude of a 40 ms window centered around the peak will be extracted. The original paper’s source analysis is not in the focus of this replication, as the placement of a dipole in the anterior cingulate does little to improve the argument for the connection between the N2 and cognitive control – these questions were investigated in other studies.

Statistical Analyses

To replicate the original study’s main effects, the following statistical tests will be conducted:

- All possible bivariate Pearson’s correlations between trait BIS, trait BAS, correct No-Go N2 amplitudes, incorrect No-Go ERN amplitudes, and resting state LFA.
- A regression analysis with trait BIS as dependent variable and LFA, trait BAS, and No-Go N2 amplitude as predictors.
- A regression analysis with trait BAS as dependent variable and LFA, trait BIS, and No-Go N2 amplitude as predictors.

These tests will be conducted on data across all replicating labs and significance will be set at $p < .02$. The statistical analysis program R will be used for all statistical tests (R Core Team, 2022). To investigate robustness of our results, each test will be conducted twice, using two different measurement scales: (1) the Carver and White scale, originally used to measure the trait BIS/BAS, and (2) the Sensitivity to Punishment and Sensitivity to Reward Questionnaire, a recently incorporated scale.. Additionally, since frequently the LFA is operationalized as the difference between F8-F7 instead of or in addition to F4-F3 (see Demerdzieva & Pop-Jordanova, 2015; Lacey & Gable, 2022; Watson et al., 2016), we will calculate an LFA for both site-pairs and use the larger difference for the group-level analysis. For each of those sets of tests, the Bonferroni-Holm method will be employed to adjust the p-values for multiple testing.

As described above, there will be some heterogeneity in EEG devices and samples between the separate replicating labs. Taking this into account, we will also perform the analyses within each lab separately, using only their individual sample, and run a random effects meta-analysis on the effect sizes (Pearson's r) from each correlation analysis. R will be used for calculation, specifically the function ‘metacor’ from the ‘meta’ package (Balduzzi, Rücker, & Schwarzer, 2019). A restricted maximum likelihood estimation method will be chosen for estimating τ^2 (a measure of variance in true effects). Forest and funnel plots will be used to visualize the results. Individual and pooled effect sizes, 95% confidence intervals, and the number of labs successfully replicating the original effect will be reported. The pooled correlation will be interpreted following Cohen’s

convention (small: r = 0.10, medium: r = 0.30, large: r = 0.50, Cohen, 1988) and significance will be set at $p < .02$. Heterogeneity between labs will be classified and interpreted according to Higgins and Thompson's I^2 statistic conventions, whereby $I^2 = 25\%$, $I^2 = 50\%$, and $I^2 = 75\%$ represent low, moderate, and high heterogeneity respectively (Higgins & Thompson, 2002).

Evaluation of the Replication

After performing the analyses as described above, the success of this replication will be evaluated based on the result of the internal metaanalysis. The replication will be considered to have been fully successful if for trait BIS, the No-Go N2 amplitude is estimated to be a predictor, but not LFA and trait BAS, and if for trait BAS, LFA is estimated to be a predictor but not the No-Go N2 amplitude and trait BIS. Within this context, trait BIS and BAS refers specifically to the scales measured in the Caver and White questionnaire, and the analyses are parallel to the original paper. The additional Sensitivity to Punishment and Sensitivity to Reward Questionnaire as well as the updated analyses go beyond the core replication attempt and will allow us to make statements about the robustness and validity of the results. If the replication is successful, and the effect can be found in the additional analysis as well, it can be considered preliminary evidence of robustness and independence from trait BIS/BAS operationalization.

Software and Code Availability

EEG and ERP data will be processed in MATLAB R2021b using EEGLAB2021.1 (Delorme & Makeig, 2004) and the following plugins: ERPLAB 9.00 (Lopez-Calderon & Luck, 2014) and SASICA (Chaumon, Bishop, & Busch, 2015). Further data analysis and visualization will be conducted in R's then current version (R Core Team, 2022). All data and code will be made available online on the Open Science Framework (as a component in #EEGManyLabs OSF page; https://osf.io/x56g9/)

Contributions

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