Effort Discounted Decision-Making in Proactive Inhibitory Control

by

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A Thesis Presented in Partial Fulfilment
of the Requirements for the Degree
Master of Science

Approved July 2018 by the
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ARIZONA STATE UNIVERSITY

August 2018

ABSTRACT

Properly deciding to engage in or to withhold an action is a critical ability for goal-oriented movement control. Such decision may be driven by expected value from the choice of action but associating physical effort may discount such value. A novel anticipatory stopping task was developed to investigate effort discounted decision process potentially present in proactive inhibitory control. Subjects performed or abstained from target reach if they believed it was a Go or Stop trial respectively. Reward was awarded to a reach, correctly timed to hit a target at the same time as the moving bar in Go trials. During the Stop trials, correctly judging to not engage in a reach from the color of the moving bar that linked to the bar's probability of stopping before the target resulted in gaining a reward. Resistive force field incurred additional physical effort for choosing to reach. Introducing effort expectedly decreased the tendency to respond at trials with higher stop probability. Surprisingly, tendency to respond increased and corresponding reaction time decreased in the trials with lower stop probability. Such asymmetric effect suggests that the value of context ineffective response is discounted, and the value of context effective response is flexibly enhanced by its associated effort cost to drive decision-process in goal-oriented manner. Medial frontal event related potential (ERP) locked to the onset of moving bar appearance reflected such effort discounted decision process. Theta band observed in Stop trials accounted for evaluation of effort and context possibly reinforcing such decision-making.

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INTRODUCTION

A baseball player may strategically choose to or not to swing at an incoming ball. However, such decision-making process underlying the engagement or disengagement in the action (Filevich, Kühn, & Haggard, 2012; Ghosh, Rothwell, & Haggard, 2014; Kühn, Haggard, & Brass, 2009) is often overlooked when studying the voluntary movement control. Any voluntary action is essentially dichotomous that there is always an option to not engage in the action. People readily surpass such sophisticated cognitive competition unconsciously. Therefore, studying the mechanism behind how people choose to or not to commence with the action known as inhibitory control may elucidate the largely unknown interaction between motor and cognitive control.

A potential bridging factor between motor and cognitive control may be effort cost (Burk, Ingram, Franklin, Shadlen, & Wolpert, 2014; Schweighofer et al., 2015). Several studies have already attempted to study decision-making in the sensory motor control domain by testing the effect of effort cost. For example, a bias toward less effortful option was observed when indicating a perceptual decision (i.e. judging collective movement direction of random dots) using an upper limb movement (Marcos, Cos, Girard, & Verschure, 2015). Furthermore, neuroimaging with fMRI has revealed the involvement of supplementary motor area and the dorsal anterior cingulate cortex when comparing the potential reward values and necessary effort levels between given choices (Klein-Flugge, Kennerley, Friston, & Bestmann, 2016).

In the present study, we have developed a novel anticipatory stopping task to assess the influence of subjective effort cost on the proactive inhibitory control (Aron, 2011; Criaud, Wardak, Hamed, Ballanger, & Boulinguez, 2012; Shadmehr,

Huang, & Ahmed, 2016). Subjects either reached into a target at correct timing or inhibited the reach depending on predicted trial type to accumulate rewards. A physical effort was introduced by setting a force field in subject's reaching workspace. The likelihood of needing to inhibit and the levels of effort anticipated were cued. Electroencephalography (EEG) was also recorded as an exploratory attempt to find medial frontal neural correlates characterizing the potential effort discounted behavior. Medial frontal area is known to capture neural activity for response inhibition (Kok, Ramautar, De Ruiter, Band, & Ridderinkhof, 2004; Ramautar, Kok, & Ridderinkhof, 2006), cost-benefit valuation (Manohar & Husain, 2016; Seitz, Franz, & Azari, 2009), and conflict (Chang, Ide, Li, Chen, & Li, 2017; Cohen & Cavanagh, 2011; Cohen & Ridderinkhof, 2013; Zavala et al., 2014). Furthermore, strong involvement of anterior cingulate cortex (ACC) was expected (Baker & Holroyd, 2011; Botvinick, 2007; Heilbronner & Hayden, 2016).

We hypothesized that imposed effort would discount the value of responding and increase the tendency for inhibition because the task incurs additional effort only for choosing to respond but provides equal opportunity for a reward in correctly choosing to respond and inhibit. Surprisingly, the response tendency did not decrease globally with the effort requirements: decision to inhibit was only enhanced during the trials with higher likelihood of movement inhibition. Trials with lower inhibition likelihood were characterized by an increasing tendency to respond. Moreover, response onset was generally earlier while slower reaction time was compensated with faster reach velocity during trials with than without effort. Event-related potentials and theta band activity were modulated accordingly with effort and inhibition likelihood of the task. We infer that effort cost may be driving

decision-making by discounting the value of response but only if that response is effortful *and* with high likelihood of being context ineffective. Conversely, effort would appreciate the value of effortful response if it is likely to be effective in the goal-directed context.

MATERIAL AND METHOD

Participants

Fifteen participants (3 females, 12 males; age: 22-37) with no history of psychiatric or neurophysical disease took part in this study. All participants gave written informed consent according to the Declaration of Helsinki. The experiment was approved by the Office of Research Integrity Assurance, Arizona State University. Participants were told that they can earn at minimum $10 and up to $20 depending on the score obtained in the experiments to encourage serious engagement in the experiment. All participants were compensated $20 regardless of the task performance at end of the experiment. Two subjects were removed from the analysis for having biased reaction time: more than 90% of reaction time observations were longer than the stop-signal delay. Another subject was removed only from the EEG time-frequency analysis due to the malfunctioning in the EEG recording during the first block of the experiment.

Experimental Set-Up

The experiment was conducted using a robotic system (KINARM End-Point Lab, BKIN Technologies). Subjects were asked to grasp the handle of the robotic system with their right hand and to maneuver it accordingly with the instructed task rule (Figure 1A). Subjects' direct view of their hand was blocked by the

horizontal screen and visual feedback of their hand was limited to a white circle (0.7cm radius) that dynamically displayed corresponding hand position under the screen. We made sure subjects were comfortably seated to have complete view of the screen as well as unrestrained workspace for their right arm.

Behavioral Task and Protocol

Subjects performed novel anticipatory stopping task. The task is a derivative of a stop-signal paradigm (Dunovan, Lynch, Molesworth, & Verstynen, 2015; Logan & Cowan, 1984; Zandbelt & Vink, 2010) which requires subjects to respond to a Go stimulus for most of trials (Go trials) but also requires them to inhibit their response for infrequent trials that presents a Stop stimulus after the Go stimulus at some delay (Stop trials). In our task, subjects were exposed to a colored bar that moved toward a white-outlined box (target) at a constant speed (10cm/s) in every trial. This colored bar functioned both as Go and Stop stimuli. Onset of the bar movement can be considered as Go stimulus and infrequent pause of the bar before it reached the target as Stop stimulus. Subjects were instructed to reach and hit the target at a same timing as the bar arrives at the target during the Go trials. Hitting the target paused movement of the bar at its current position and allowed subjects to reflect on their reach timing accuracy. On the other hand, subjects were instructed to inhibit their movement and stay at a starting position during the Stop trials. These two types of trials were presented at randomized order during the experiment.

Subjects earned a point whenever they successfully completed the task given a trial type. A point was deducted otherwise. During the Go trials, subjects earned a point by stopping the moving bar as close to the center of the target as possible. The

threshold implemented was ±0.5cm. During the Stop trials, suppressing their movement and not leaving the starting position indicated by the green circle (1cm radius) was considered successful. Subjects were asked to maximize the score by correctly executing the required action during each trial.

Subjects were instructed to execute the correct action that corresponds to the trial type based on two types of visual cues. One of the cues was the color of the moving bar which represented the probability of the bar stopping (P(stop) cue, Figure 1B). The colors used were gray, cyan, magenta, yellow, and orange and their associated stop probabilities were 0, 0.15, 0.4, 0.6, and 0.85 respectively. The gray colored bar was used only during the first block and subjects were explicitly notified that it signifies the Go trial. All other colors were presented during the second and the third block, but their associated stop probabilities were not revealed. Subjects were told to deduce associated stop probabilities through trial-and-error during the second block. Another cue was a blue bar in a gray vertical rectangle (effort cue, Figure 1C) that informed subjects about the strength of the velocity-dependent resistive force field. The height of the blue bar corresponded with the three levels of force field strength: low, medium and high. The force field was defined as $F = B \times v$ where $B = (0, 0, 0, a)$ is the scaling factor and $v = (v_x, v_y)$ is the two-dimensional velocity of the hand. The force amplitude parameter was set as $a = -15, -30, -45$ with the unit of $N \cdot s/m$. The effort cue and the force field were presented before the target and the moving bar appeared on the screen. Importantly, the effort cue was only given during the final block of the experiment and all other blocks had force field turned off.

The experiment was implemented in three-level block design which prepared subjects one after another for the novel anticipatory stopping task. Importantly, subjects were given new instruction at the beginning of each block and didn't have *a priori* knowledge about the upcoming task in the following blocks. The first block consisted of 50 trials of Go trials. We informed subjects that all trials are Go trials and instructed them to treat this block as a practice round for learning the optimal reach timing and the basic flow of the trials. The second block had total of 320 trials of both Go and Stop trials. Stop probability used were 0.15, 0.4, 0.6 and 0.85. Subjects were only informed that the bar colors represent the probability of trial being a Stop trial. We asked subjects to learn the Stop trial likelihood associated with the color through this block. The final block was similar to the previous block except the effort component was introduced. We emphasized that there will be a resistive force applied when making a reach and the effort cue will be displayed to signal the relative strength of the anticipated force field. Because this block contained Go and Stop trials with the same P(stop) cues from the previous block, we asked subjects to use the learned likelihood to make correct actions. There were 480 trials in this final block. Subjects were given a break every 80 trials in block 2 and 3.

The basic sequence within the trial is the same for all block (Figure 1D). Each trial began by moving the robotic handle to the starting position. Following the stay in the starting position for 500ms, a white fixation cross was displayed for 500ms to signal subjects to get ready for the upcoming task. Then two key visual stimuli, the target and the colored bar, were presented at a variable delay. The target and the bar appeared 9cm and 2cm away from the starting position in the action space respectively. The bar stayed at the initial position for 250ms and began moving

vertically toward the target at a constant speed. During the Go trials, the bar reached the center of the target after 700ms. The bar stopped after 475ms (Stop signal delay or SSD) from the onset of the movement during the Stop trials. Target changed color to green when subject made correct response. Subjects were given effort cue after the presentation of a fixation cross for 1000ms during the final block. Subjects started with 200 points at the beginning of each block. The accumulated score was displayed at the end of every trial to allow performance tracking.

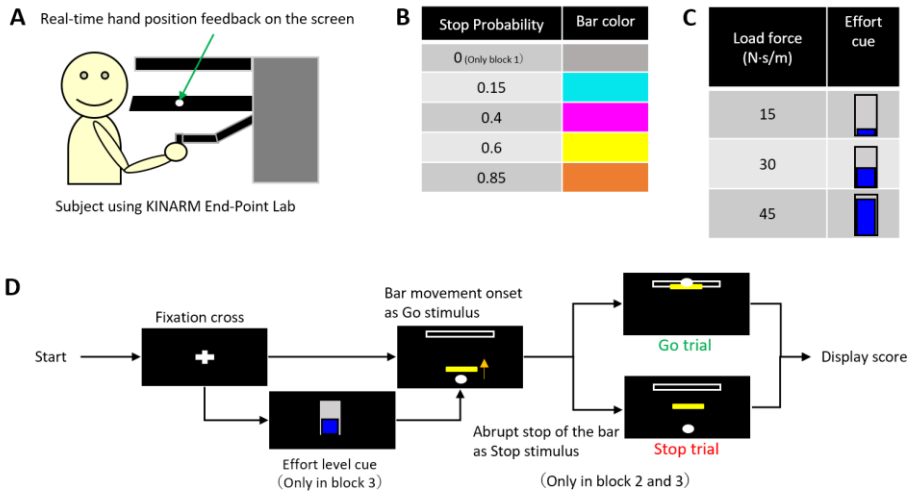

Figure 1. Experimental protocol. **A,** A simple diagram of an experimental set-up. **B,** Probability of encountering Stop trial and corresponding bar colors. **C,** Visuals of the effort cue and its corresponding load magnitude. **D,** Subjects receives fixation cross as the first visual stimulus. The effort cue will then be displayed unless it is block 1 or 2. The colored bar will always move toward the target at a constant speed. Subjects must reach into the target simultaneously as the bar arrives at the target during the Go trials. Subjects must refrain from committing to a reach during the Stop trials. The bar pausing before arriving at the target signals the Stop trial. Gain/loss of points will be displayed at the end of the trial.

EEG Acquisition and Data Preprocessing

EEG activity was continuously recorded for each block using 64-channel system (actiCAP slim, Brain Products) with mastoid reference. The sampling frequency was 5000Hz while electrode impedance was maintained below 10kΩ for

all subjects. Offline preprocessing was performed using EEGLAB (Delorme & Makeig, 2004) and custom written MATLAB (Natick, MA, USA) scripts. First, acquired EEG signals were down sampled to 250Hz and band pass filtered with cut-off frequency of 0.8Hz and 55Hz. EEG data were then re-referenced to average reference. Initial epochs included 0.75 seconds before and 5.25 seconds after the fixation cross onset. Epoch and channel rejection were done manually by visual inspection. An Independent Component Analysis (ICA) was then applied on all epochs using the standard EEGLAB function with extended infomax option. ICA components subjected to artifacts such as blinking, eye movement and muscle contraction were removed with visual inspection. Missing electrode locations due to earlier channel rejection were interpolated with artifact removed ICA-weighted EEG data. Spatial resolution in terms of scalp surface potential was enhanced using current source density (CSD) estimates through 4th order spherical spline algorithm provided by CSD toolbox (Kayser & Tenke, 2006). Once the preprocessing was completed, these data were re-epoched using different time-locking events and time window length as needed for further analysis.

Data Analysis

All blocks from the experiment can be separated into two phases within each block: learning and post-learning. First 30 trials from the first block were considered as the learning phase for the optimal reach timing as well as the basic trial flow. In the second and the third block, first 160 trials were considered as the learning phase for the P(stop) cues and force field adaptation, respectively. We believe this number of trials is sufficient to have subjects get exposed to each P(stop) cue and allow them

to learn the associated likelihood during block 2 since roughly 40 trials of each P(stop) condition should appear within 160 trials random presentation. Similarly, we believe that first 160 trials of block 3 (random mix of trials present about 53 trials of each effort level) should be sufficient to make subjects become comfortable with the effort cue and the actual force field. We focused both EEG and behavioral analysis on the data obtained from the post-learning phase. An advantage for such method is that it allows us to remove surprise or adaptive effect that may confound the findings. Also, because learning is not within the scope of our study, any potential noise related to it should be eliminated. Although disregarding large portion from available data may risk statistical power, implementing learning stage in the experiment has distinct benefit for our study. Because we are concerned about the quantitative effect (i.e. change in inhibition tendency and related electrophysiology) of cognitive control determined by the subjective valuation of predicted outcome and perception of task context, we intended to allow subjects to form their own belief with sufficient exposure to the conditioning stimuli and the task environment. Therefore, the data obtained from the post-learning phase should reflect the naturally occurring behavioral and electrophysiological phenomena normalized to individual's cognitive process.

Behavioral Analysis

We were interested in probability of inhibition, reaction time and peak reach velocity. The probability of inhibition elucidates the decision tendency given the context of stop probability and the effort requirement. Change in the decision tendency would signify the change in proactive control ascribed to the subjective

context valuation. Reaction time quantified the time subjects took to process the decision. Previous literatures suggest computation dictating motor planning is reflected in the time people took to commit movement (Michaels, Dann, Intveld, & Scherberger, 2015). For instance, people tends to respond quicker when they anticipate or have the foreknowledge of the outcome (Liebrand, Pein, Tzvi, & Krämer, 2017). Therefore, reaction time is an indirect measure of conflict processing which is a critical component of our experiment. Finally, the peak reach velocity represents the maximum physical effort cost subjects decided to undertake. Only the peak velocities obtained from successful Go trials were evaluated because the overt reach demonstrated in this condition should reflect the most deliberate reward-effort tradeoff.

Subjects were considered to have responded when they left the starting position. The probability of inhibition was computed for each stop probability level: the number of inhibited trials divided by the total number of encountered trials for each stop probability. The reaction time was defined as the time subjects took to leave starting position counting from the bar movement onset. Peak reach velocity was found from the hand movement in positive y-direction (i.e. toward target).

Event-Related Potentials

We analyzed frontocentral event-related potential (ERP) by focusing on the signal amplitude obtained from the channel FCz. Time window locked to the bar appearance was re-epoched from the preprocessed EEG signal. This epoch allowed us to observe the preparatory activity present after the P(stop) cue is revealed to the subject and the on-going decision-making process present during the bar movement.

We identified two unique features in this part of the signal from block 2 and 3, denoted as BarOn-N2 and BarStart-N1. The window for BarOn-N2 was centered at 200ms after the bar appearance and BarStart-N1 was centered at 50ms after bar movement onset. N2 and N1 are negative-going potential occurring after about 200ms and 100ms in response to a stimulus respectively. These two features were statistically compared between stop probabilities and blocks using the mean computed across 100ms window centering at corresponding latencies.

Note that ERP characterized in our analysis was generated from surface Laplacian transformed signals, CSD, instead of conventional sum of scalp potentials obtained at specific channel. An approach to analyze ERP using CSD has been successfully performed in previous literatures on response inhibition (Krämer, Knight, & Münte, 2011; Rangel-Gomez, Knight, & Krämer, 2015; Schevernels et al., 2015). Moreover, previous account on response inhibition studied using stop-signal task has reported temporally close activities in both frontal and parietal areas (Greenhouse & Wessel, 2013; Ramautar et al., 2006). ERP characterized using CSD may disambiguate medial-frontal activity better than scalp potential since the primary advantage of using CSD is its spatial specificity.

Time-Frequency Analysis

We examined EEG activities from medial frontal area by focusing on the time-frequency representation obtained from channel FCz. Time-frequency decomposition was done using Morlet Wavelet transformation using EEGLAB function with 45 linearly spaced bins from 2Hz to 90Hz. The minimum and maximum cycles of wavelet used were 4 and 10 cycles respectively. Computed time-

frequency powers were baseline corrected in reference to the mean power obtained from 150ms time window prior to the appearance of fixation cross in the first block. Edge artifacts were removed by cutting off 100ms of data from the beginning and the end of each time-frequency representation of the epoch. Theta (4-8Hz) and alpha (9-12Hz) band were the frequency band of interest because previous studies have confirmed their relation to conflict, reward and performance evaluation and processing (Chang et al., 2017; Gruber, Watrous, Ekstrom, Ranganath, & Otten, 2013; Hajihosseini & Holroyd, 2013; Kawasaki & Yamaguchi, 2013). In addition to the same epoch examined using ERP, another time window time-locked to the bar stop timing during the Stop trials from block 2 and 3 were examined. This epoch should reflect the monitoring mechanism in respect to prediction and valuation formulated from the given stop probability and effort information. Two 100ms segments after the bar appearance and bar movement onset were chosen for analyzing preparatory activity. We labeled two segments as Post-BarOn and Post-BarStart. Post-BarOn segment spanned from 50ms to 150ms in respect to the bar appearance while Post-BarStart segment spanned the same time period as BarStart-N1. Monitoring activity was also assessed using the theta band power obtained from stop-signal locked time window. Grand mean band powers were computed for each stop probability group without distinguishing the inhibition performance. Combining both successful and unsuccessful inhibition trials allowed robust representation of context monitoring irrespective to subjects' motor output. A 200ms time window centering at 350ms was chosen by visual inspection of the waveform and the mean across the time window were computed for each stop probability group.

RESULT

Probability of Inhibition

The learning of stop probabilities associated with P(stop) cues was confirmed by one sample T-test applied on probability of successful Stop trial inhibition from block 2 against corresponding stop probabilities (P(stop)=0.15: $t_{(12)}$=-0.52, p=0.612; P(stop)=0.4: $t_{(12)}$=-1.35, p=0.202; P(stop)=0.6: $t_{(12)}$=-1.13, p=0.282, P(stop)=0.85: $t_{(12)}$=0.48, p=0.638). Inhibition tendency for different stop probabilities were quantified by computing proportion of response inhibition committed for trials subjects encountered with each P(stop) cues (Figure 2A). Having the effort requirement apparently increased the tendency to refrain from reaching in higher stop probabilities. Counter intuitively, the effort requirement increased the tendency to reach in lower stop probability trials. The trend was consistent across all effort levels as effort magnitude had no modulatory or scaling effect (Figure 2B). Such observation was validated with a generalized linear mixed model using a logit link with a binomial response function and subject dependent random effect. Effort levels were collapsed and interaction effect between stop probability and block was confirmed with type III Wald Chi square test (P(stop): $\chi^2(3)$=555.99, p<2.2e-16; block: $\chi^2(1)$=0.36, p=0.55, P(stop)-block: $\chi^2(3)$=50.7, p=5.7e-11). The predicted values were estimated using a least squared method (see Appendix). Pairwise comparison with Turkey adjustment on predicted values revealed significant change from block 2 to block 3 at all stop probabilities except for stop probability of 0.4 with p=0.96.

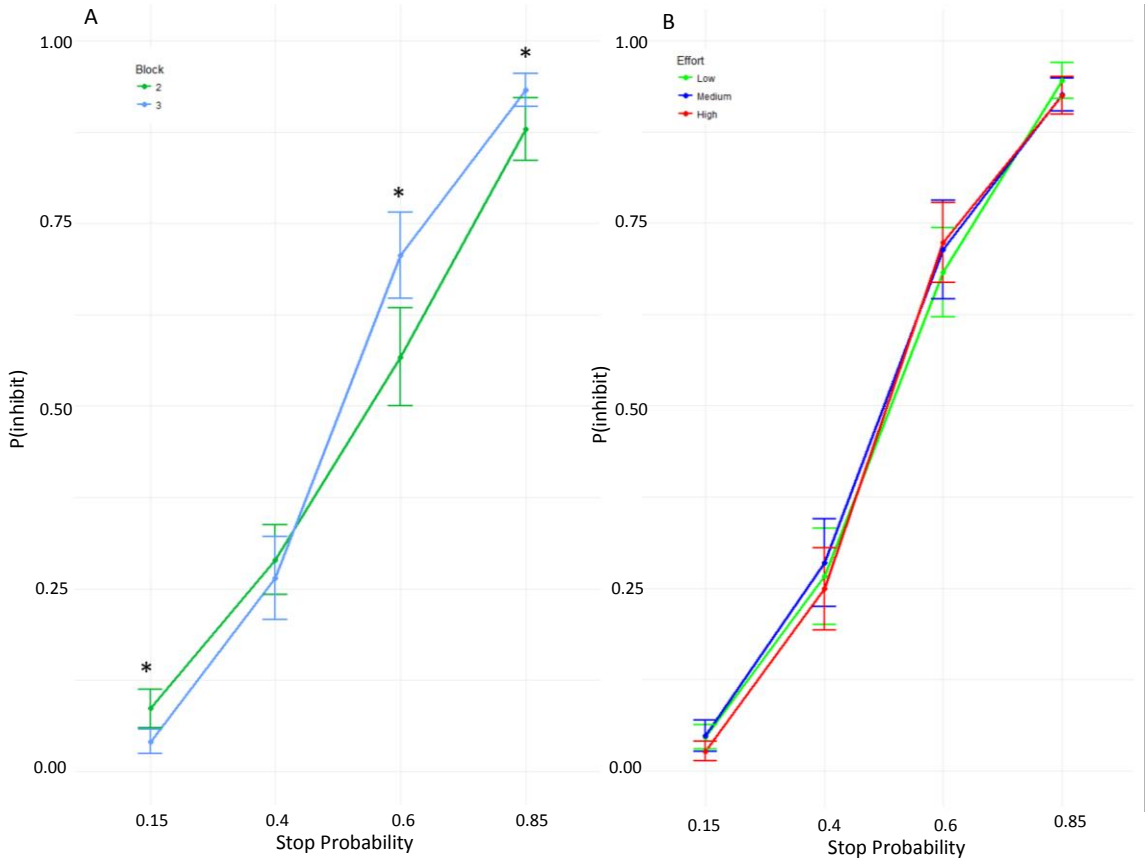

Figure 2. Probability of inhibition. **A,** Mean probability of inhibition with different stop probability. Addition of effort requirement raised the inhibition tendency in higher stop probabilities while asymmetrically lowered it in smaller stop probabilities. **B,** Mean probability of inhibition in block 3 grouped by effort levels. Effort levels didn't yield distinct difference in the response tendency.

Reaction Time

Slowing down in reaction time was observed when the conditions requiring to potentially stop was added (Table 1, See Appendix). One-way ANOVA following with a Tukey' test verifies significance of such change between the reaction time from block 1 and from each levels of stop probabilities in following blocks (block 1 and 2: $F_{(4,55)}$=5.188, p=0.001; block 1 and 3: $F_{(4,55)}$=4.754, p=0.002). Across the conditions with probable encounter of Stop trials, the mean reaction times are slightly shorter with effort than without effort for all stop probabilities (Figure 3B). A linear mixed

effect model was constructed to evaluate this effect of effort requirements on the reaction time. Effort levels were collapsed as it had no effect in block 3. The model considered fixed effect from interaction of stop probabilities and the block along with random effects from subjects. Type III Wald Chi square test confirmed the significant effect of effort requirement on reaction time (P(stop): $\chi^2(3)=73.526$, $p=7.50e\text{-}16$; block: $\chi^2(1)=8.769$, $p=0.003$; P(stop) and block: $\chi^2(3)=12.121$, $p=0.007$). Pairwise comparison of predictions generated with least squared mean method identified statistically significant decrease in reaction time from block 2 to block 3 at stop probabilities of 0.15 but not at other stop probabilities (block 2 and 3: P(stop)=0.15, $p<0.0001$; P(stop)=0.4, $p=0.306$; P(stop)=0.6, $p=0.598$; P(stop)=0.85, $p=1.000$). Interestingly, the model predicted that there is no statistically significant difference between reaction time obtained at stop probability of 0.4 and 0.6 as well as 0.15 and 0.85 within block (P(stop)=0.4 and 0.6: block2, $p=0.7709$; block 3, $p=0.7197$; P(stop)=0.15 and 0.85: block2, $p=0.9053$; block 3, $p=0.3967$). This may be indicative of similarity in conflict processing due to clear and ambiguous stop probability cues that is also sustained regardless of the effort manipulation. Conversely, the significant difference between reaction time from stop probability of 0.15 and 0.6 was maintained across the block (P(stop)=0.15 and 0.6: block 2, $p=0.0126$; block 3, $p<0.0001$). The decrease in reaction time at stop probability of 0.15 over the block gave rise to a distinction between the reaction time at stop probability of 0.4 (P(stop)=0.15 and 0.4: block 2, $p=0.3556$; block 3, $p<0.001$). Meanwhile, significant difference between stop probability of 0.6 and 0.85 dissipated across the blocks (P(stop)=0.6 and 0.85: block 2, $p=0.0269$; block 3, $p=0.6302$).

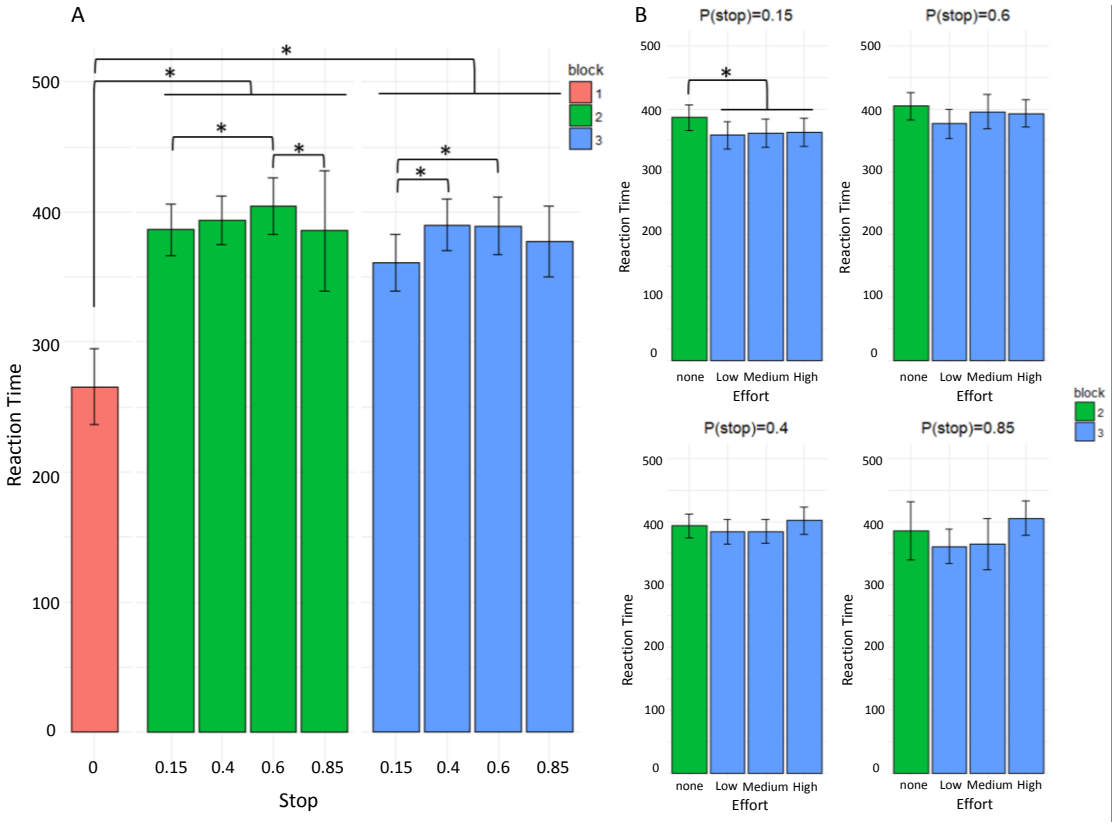

Figure 3. Reaction time **A,** Mean reaction time grouped by block and stop probabilities. Block 1 (Go only) has much shorter reaction time than block 2 or 3. Block 3 (with effort) had slightly shorter reaction time overall than block 2 (without effort). **B,** Mean reaction time from block 2 and 3 separated by effort levels. Addition of effort component affected the reaction time, but the effort magnitude didn't have statistically significant effect.

Peak Reach Velocity

There was no significant change observed between the mean peak velocities from successful Go trials from P(stop)=0.15 conditions in block with and without effort components. Pairwise T-test was used to compare mean peak velocities by subjects. (P(stop)=0.15: $t_{(12)}$=1.238). However, addition of effort component induced change in the relationship between the reaction time and the peak velocity generated during the reach. Quadratic curve was fitted on the peak velocity in respect to corresponding reaction time obtained from successful Go trials in

P(stop)=0.15 conditions (block 2: R^2=0.839, $F_{(2,234)}$=613.8; block 3: R^2=0.814, $F_{(2,584)}$=1279, see Appendix). Two curves had matching trend where peak reach velocity increase nonlinearly as the time subjects took to response increased (Figure 3). Interestingly, two curves begin to diverge as the reaction time increased. Such effect was confirmed by adding block as a predicting variable to the regression model (R^2=0.819, $F_{(3,820)}$=1238, see Table 1 in Appendix). Only the peak reach velocities observed at P(stop)=0.15 condition was analyzed because it had the largest numbers of successful Go trials from each subject and had the effort induced change in response tendency confirmed from probability of inhibition. Also, note that the effort levels were considered to have no effect in peak reach velocity since it didn't have effect in probability of inhibition and reaction time. Same assumption was used in following EEG analysis.

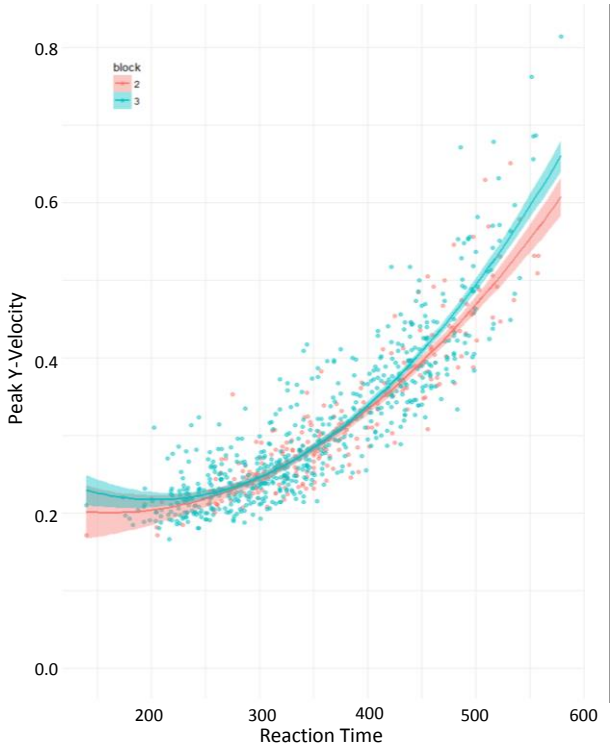

Figure 4. Peak velocity during successfully reached trials at P(stop)=0.15 condition. Fitted quadratic curved for Block 2 (without effort) and 3 (with effort) begins to diverge at longer reaction time.

EEG During Preparatory Period

Mean ERP waveform grouped by stop probabilities were showing distinct negative going peak approximately after 200ms of bar appearance (Figure 5A). This BarOn-N2 appears to be scaled by stop probabilities: the peak amplitude is larger for higher stop probabilities (Figure 5B, left). The separation of the waveform became clearer with the addition of effort component. Such effect was especially pronounced between the P(stop)=0.4 and 0.6. Although an interaction effect of the stop probability and the block was not observed, statistically significant difference was shown for the mean amplitude of BarOn-N2 across stop probabilities and blocks (Stop probability: $F_{(3,96)}$=15.128, p=3.88e-8; Block: $F_{(1,96)}$=3.946, p=0.0498; Stop probability and block: $F_{(3,96)}$=1.087, p=0.36). Post-hoc pairwise T-test confirms the effort requirement effect specifically at P(stop)=0.6 and 0.85 (P(stop)=0.15: $t_{(12)}$=-0.259, p=0.800; P(stop)=0.4: $t_{(12)}$=0.526 p=0.61; P(stop)=0.6: $t_{(12)}$=3.860, p=0.002, P(stop)=0.85: $t_{(12)}$=2.279, p=0.04). Another recognizable negativity is present around 50ms after the bar starts moving in the grand mean waveform. Mean amplitude in this BarStart-N1 window shows clear separation between lower and higher stop probabilities (Figure 5B, right). A two-way factorial ANOVA indeed confirms the effect by the stop probability. However, interaction effect with the block and the effect from block on its own didn't cause statistically significant difference. (Stop probability: $F_{(3,96)}$=23.710, p=1.44e-11; Block: $F_{(1,96)}$=0.065, p=0.8; Stop probability and block: $F_{(3,96)}$=1.161, p=0.329). A post-hoc Tukey's test bolstered the observed separation in the mean amplitude between the higher and lower stop probabilities: Only the pairs of P(stop)=0.15 and 0.4 and P(stop)=0.85 and 0.4 had p>0.05. Although block effect was not present globally, a significant increase in mean

amplitude with the addition of effort component was confirmed at P(stop)=0.15 with paired T-test ($t_{(12)}$=-3.225, p=0.007).

Observation of the same epoch in time-frequency domain shows intense activity at theta and alpha frequency (Figure 6A). Slow but gradual increase in the signal can be seen in theta and alpha band (Figure 6B). Also, the waveform from these two bands were very similar throughout this epoch. Two-way factorial ANOVA didn't show the effect from stop probability, block or the interaction between the two at neither Post-BarOn or Post-BarStart period (See Table 6 and 7 in Appendix).

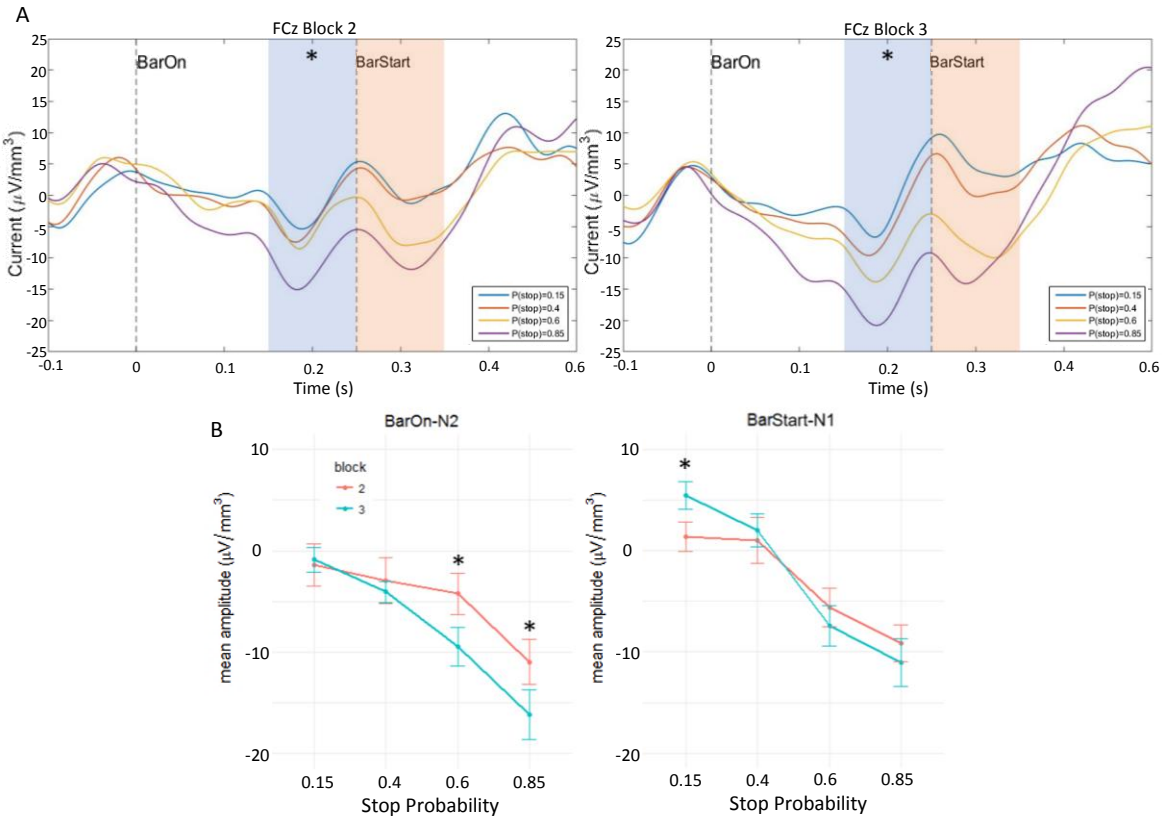

Figure 5. ERP time-locked to bar display onset. **A (top row),** Mean ERP waveform grouped by stop probability. Left plot represents block 2 (without effort) and right plot represents block 3 (with effort). Blue and orange shading corresponds to N2 and N1 period respectively. **B (bottom row),** Mean ERP amplitude at BarOn-N2 and BarStart-N1 time widow. Magnitude of N2 scaled with the stop probability and the its negativity increased for the higher stop probabilities when effort component was added. Higher and lower stop probabilities show clear distinction in the polarity while effort requirement enhanced the positivity at P(stop)=0.15.

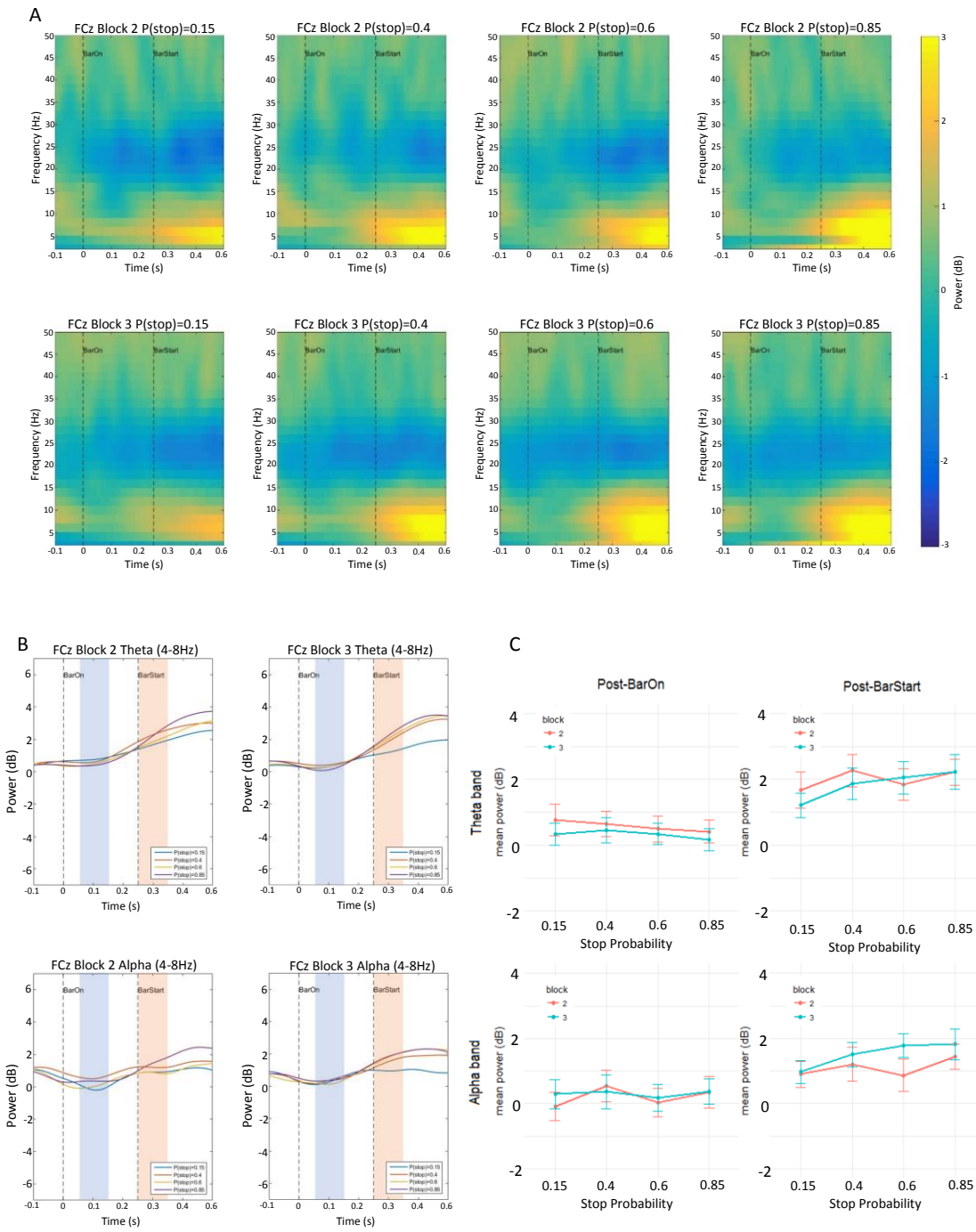

Figure 6. Time-frequency representation time-locked to bar display onset. **A. (Top row),** Spectrogram. Top and bottom row corresponds to block 2 and 3 respectively. The plot is arranged from increasing order of stop probability from left to right. **B (Bottom row left),** Mean band power waveform grouped by stop probability. Plots in the left column represents block 2 (without effort) and the right column represents block 3 (with effort). Plots on top and bottom rows represent the theta band and alpha band power respectively. Blue and orange shading corresponds to Post-BarOn and Post-BarStart period respectively. **C (Bottom row, right)** Mean band power at Post-Baron and Post-BarStart time window. Both theta and alpha band increases its magnitude gradually from Post-BarOn to Post-BarStart.

EEG During Stop-Signal Monitoring Period

Time-frequency decomposition of stop-signal locked epoch also demonstrated strong presence of theta activity (Figure 7A). Such phenomenon was robustly present even with low time-frequency resolution manifested due to the lower numbers of Stop trial observations in P(stop)=0.15. Extracted theta band power showed peak at latency of about 300ms. Interestingly, these peaks were clearly scaled by stop probability: lower the stop probability, larger the peak (Figure 7B). Mean obtained from the segment around the peak characterized gradual decrease in the band power with the increase in stop probability. Notably, its magnitude globally decreased with the addition of effort component (Figure 7C). Two-way factorial ANOVA demonstrates strong effect from the stop probability and the addition of effort component. (Stop probability: $F_{(3,88)}$=17.704 p=4.49e-9; Block: $F_{(1,88)}$=5.723, p=0.019; stop probability and block: $F_{(3,88)}$=0.016, p=0.100). Post-hoc Tukey's test for stop probability showed p<0.05 for all pairings except P(stop)=0.15 and 0.4 and P(stop)=0.6 and 0.85.

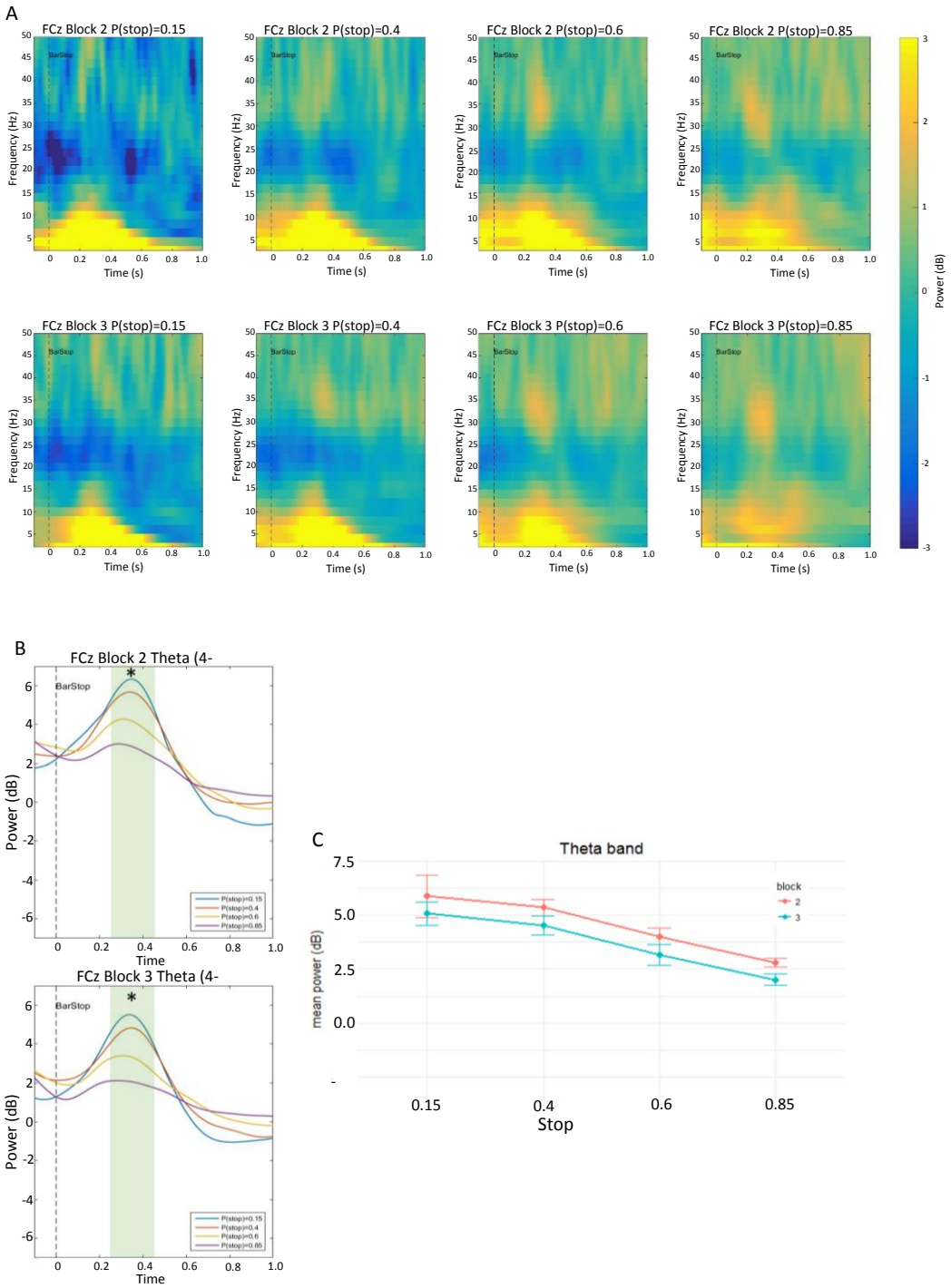

Figure 7. Time-frequency representation time-locked to stop-signal in Stop trials. **A. (Top),** Spectrogram. Top and bottom row corresponds to block 2 and 3 respectively. The plot is arranged from increasing order of stop probability from left to right. **B (Bottom, left),** Mean band power waveform grouped by stop probability. Clear separation of peak magnitude by stop probabilities are present in both block 2 (left, without effort) and block3 (right, with effort). **C (Bottom, right),** Mean theta band power around peak. Gradual inverse relation is shown between theta band power and stop probability and its magnitude is globally scaled down with the addition of effort component. The time window used corresponds to the green shading in above plots.

DISCUSSION

We developed a novel anticipatory stopping task to assess potential effort discounted decision process underlying the inhibitory control. Subjects were given trials where correctly deciding to engage in or to abstain from a motor response (i.e. timed target reach) results in earning a reward. We initially hypothesized that adding physical load (i.e. effort) to reach would discount the value of response and predispose subjects to inhibit globally across all conflict combinations (probability levels by effort levels). However, associating physical effort with the response increased the tendency to inhibit only when the probability of earning a reward by not engaging was higher. On the other hand, tendency to generate motor response was increased when earning a reward was more likely by responding even though it required to expend more effort cost. Therefore, instead of unimodally discounting the action directly associated with the imposed motor cost, the effort requirement flexibly discounted the context ineffective choice: the choice that was less likely to yield reward. By contrast, effortful choice was enhanced when it is context effective.

A natural follow-up question to the above-mentioned result would be, how does the brain achieve such flexible decision? One hypothesis is effort discounting may be driving the control allocation, i.e., the mechanism of weighing one action over another and adjusting the intensity of control over it (Shenhav, Botvinick, & Cohen, 2013). Control allocation is often discussed in terms of conflict and value (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Dixon & Christoff, 2012). Some argue that people are inclined to allocate control to less conflicting choice of action (Dreisbach & Fischer, 2012). However, this framework does not explain our observation of increase in the tendency to respond during the effortful condition

because choosing to expend more energy to attain reward should be conflicting when you still have a chance to earn a reward by not expending the energy. It has also been proposed that control is appropriated to the motor plan with higher estimated benefit (Hwang, 2013). Our behavioral and neurophysiological results fit the latter idea better.

Not only did effort requirement induced change in decision tendency, it may also have improved the task performance. Counterintuitively, the condition with the lowest stop probability yielded reduction in reaction time when the effort component was introduced. This may suggest quicker resolution of conflict. Also, it possibly signifies the adaptation to the new task context (Abrahamse & Verwey, 2008). Commencing the reach early with short reaction time can potentially eliminate extra metabolic expenditure by avoiding the risk of making fast reach in velocity dependent force field. Indeed, mean peak reach velocity from successful Go trials in lower stop probability condition didn't differ between with and without effort component. This implies that subjects have maintained consistency in deliberate reach velocity. We saw that peak reach velocity increased quadratically as the reaction time increased. Moreover, comparatively faster reach was exhibited in effort imposed than effort not imposed condition as subjects took more time to respond. Behavioral change observed potentially signifies allocating more control to response over inhibition in order to maximize reward in the effortful environment.

Neural signatures obtained also bolsters the value-based control allocation. BarOn-N2 gained negativity as the stop probability increased and such effect was enhanced for higher probability when the physical effort cost was introduced. This possibly represents a phenomenon of increasing gain on the control signal that

suppresses the motor output based on the expected value of inhibition. In other word, effort is discounting the value of responding. Idea that N2 is representing the control allocation to inhibition agrees with the previous accounts on enhanced N2 found during conflicting situations which may require more attentive inhibitory control to not release motor output before resolving response conflict (Donkers & Van Boxtel, 2004; Enriquez-Geppert, Konrad, Pantev, & Huster, 2010; Groom & Cragg, 2015). BarStart-N1 following BarOn-N2 may be distinguishing the effective choice of an action in respect to stop probability and reward by its polarity. Higher stop probability conditions where inhibition is more context effective than response maintained its negativity at BarStart-N1. Suppose gaining negatively in ERP reflects the control allocation to the inhibition, gaining positivity may reflect the opposite. Indeed, ERP at lower probability conditions where response is more context effective than inhibition increased their positivity. P(stop)=0.15 condition had particularly significant increase in positivity with the addition of effort. Note that barStart-N1 may potentially be overlapping with P3 since it its peak appears around 300ms after the bar appearance. Observed negativity may be due to Go signal (i.e. bar movement) invoking attention (van Noordt, Desjardins, & Segalowitz, 2015). Increasing theta activity during the BarOn-N1 period also supports attentional modulation since medial frontal negativity is also related to attentional theta activity (Van Noordt, Campopiano, & Segalowitz, 2016). Intensifying the control signal that generates motor output may lead to various goal-oriented behavioral changes observed at this condition. Assuredly, cue-locked P3 seen in Go/No-Go task may be related to movement-related potential (Verleger, Paehge, Kolev, Yordanova, & Jaśkowski, 2006).

Idea of control allocation driven by effort cost stems on the presumption that subjects have learned context dependent effectiveness of response and inhibition. A potential reinforcement learning process can be inferred through theta activity in conjunction to the stop-signal (i.e. bar stop). Theta power had a distinguishing peak scaled by the stop probabilities which were also globally diminished when effort cost was introduced. We infer that theta power may account for the value of alternative choice of control in respect to the context effective control predicted from given stop-probability cue. Stop-signal directly informs subjects that it is a Stop trial and resolves the earlier decision conflict. Therefore, discrepancy is large when predicted optimal control was to respond while it is small when inhibition was predicted. Such discrepancy or prediction error may correspond to the value of alternative choice of control be reinforced from trial-by-trial Stop trial experience. Thus, the mean theta activity of all Stop trials inversely increased with the stop probability. Furthermore, effort cost would also contribute to such value computation. The alternative option to be reinforced from stop-signals are consequently context ineffective. In terms of effort discounting proposed from our experiment, value should depreciate if the action associated with is context ineffective. Thus, we see the shifts down in the theta power peaks. Idea that there may be neural signature expressing value of alternative option of control may explain the exploration behavior. Dorsal anterior cingulate cortex is proposed to be involved in monitoring outcome to shift to exploration from exploitation (Aston-Jones & Cohen, 2005; Daw, O'Doherty, Dayan, Seymour, & Dolan, 2006). Furthermore, frontal theta activity is reported to be related to exploration under uncertain situation (Cavanagh, Figueroa, Cohen, & Frank, 2012). Lack of significant activity in theta band during the preparatory

period may be because of theta power modulation occurred in relative to the prediction generated.

Finally, future work should consider examining the EEG topography of ERP activity observed in the preparation period and frequency activity observed in monitoring period. Such approach may clarify if modulation driven by effort cost in the two different phases (i.e motor preparation and monitoring phase) of the task corresponds to each other locally. Furthermore, trial-by-trial analysis on the frontal theta band activity may also be valuable. This may give supplementary insight into evaluation process in respect to reinforcement and exploration behavior. In terms of experimental design, implementing higher load or larger difference between load levels may capture effort level effect that we didn't observe. It would also be interesting to study how observed tendency change by also imposing a physical effort to inhibition. A force pulse perturbation or repulsive force field are good candidate for such design implementation.

REFERENCE

Abrahamse, E. L., & Verwey, W. B. (2008). Context dependent learning in the serial RT task. *Psychological Research*, *72*(4), 397–404. https://doi.org/10.1007/s00426-007-0123-5

Aron, A. R. (2011). From reactive to proactive and selective control: developing a richer model for stopping inappropiate responses. *Biological Psychiatry*, *69*(12), 55–68. https://doi.org/10.1016/j.biopsych.2010.07.024.From

Aston-Jones, G., & Cohen, J. D. (2005). AN INTEGRATIVE THEORY OF LOCUS COERULEUS-NOREPINEPHRINE FUNCTION: Adaptive Gain and Optimal Performance. *Annual Review of Neuroscience*, *28*(1), 403–450. https://doi.org/10.1146/annurev.neuro.28.061604.135709

Baker, T. E., & Holroyd, C. B. (2011). Dissociated roles of the anterior cingulate cortex in reward and conflict processing as revealed by the feedback error-related negativity and N200. *Biological Psychology*, *87*(1), 25–34. https://doi.org/10.1016/j.biopsycho.2011.01.010

Botvinick, M. M. (2007). Conflict monitoring and decision making: Reconciling two perspectives on anterior cingulate function. *Cognitive, Affective and Behavioral Neuroscience*, *7*(4), 356–366. https://doi.org/10.3758/CABN.7.4.356

Botvinick, M. M., Braver, T. S., Barch, D. M., Carter, C. S., & Cohen, J. D. (2001). Conflict monitoring and cognitive control. *Psychol Review*, *108*(3), 624–652. https://doi.org/10.1037/0033-295X.108.3.624

Burk, D., Ingram, J. N., Franklin, D. W., Shadlen, M. N., & Wolpert, D. M. (2014). Motor effort alters changes of mind in sensorimotor decision making. *PLoS ONE*, *9*(3). https://doi.org/10.1371/journal.pone.0092681

Cavanagh, J. F., Figueroa, C. M., Cohen, M. X., & Frank, M. J. (2012). Frontal theta reflects uncertainty and unexpectedness during exploration and exploitation. *Cerebral Cortex*, *22*(11), 2575–2586. https://doi.org/10.1093/cercor/bhr332

Chang, A., Ide, J. S., Li, H., Chen, C., & Li, C.-S. R. (2017). Proactive Control: Neural Oscillatory Correlates of Conflict Anticipation and Response Slowing. *ENeuro*, *4*(3), e0061–17.2017. https://doi.org/10.1523/ENEURO.0061-17.2017

Cohen, M. X., & Cavanagh, J. F. (2011). Single-trial regression elucidates the role of prefrontal theta oscillations in response conflict. *Frontiers in Psychology*, *2*(FEB), 1–12. https://doi.org/10.3389/fpsyg.2011.00030

Cohen, M. X., & Ridderinkhof, K. R. (2013). EEG Source Reconstruction Reveals Frontal-Parietal Dynamics of Spatial Conflict Processing. *PLoS ONE*, *8*(2). https://doi.org/10.1371/journal.pone.0057293

Criaud, M., Wardak, C., Hamed, S. Ben, Ballanger, B., & Boulinguez, P. (2012). Proactive inhibitory control of response as the default state of executive control. *Frontiers in Psychology*, *3*(MAR), 1–13. https://doi.org/10.3389/fpsyg.2012.00059

Daw, N. D., O'Doherty, J. P., Dayan, P., Seymour, B., & Dolan, R. J. (2006). Cortical substrates for exploratory decisions in humans. *Nature*, *441*(7095), 876–879. https://doi.org/10.1038/nature04766

Delorme, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9–21. https://doi.org/10.1016/j.jneumeth.2003.10.009

Dixon, M. L., & Christoff, K. (2012). The Decision to Engage Cognitive Control Is Driven by Expected Reward-Value: Neural and Behavioral Evidence. *PLoS ONE*, *7*(12). https://doi.org/10.1371/journal.pone.0051637

Donkers, F. C. L., & Van Boxtel, G. J. M. (2004). The N2 in go/no-go tasks reflects conflict monitoring not response inhibition. *Brain and Cognition*, *56*(2 SPEC. ISS.), 165–176. https://doi.org/10.1016/j.bandc.2004.04.005

Dreisbach, G., & Fischer, R. (2012). Brain and Cognition Conflicts as aversive signals. *Brain and Cognition*, *78*(2), 94–98. https://doi.org/10.1016/j.bandc.2011.12.003

Dunovan, K., Lynch, B., Molesworth, T., & Verstynen, T. (2015). Competing basal ganglia pathways determine the difference between stopping and deciding not to go. *ELife*, *4*(September 2015), 1–24. https://doi.org/10.7554/eLife.08723

Enriquez-Geppert, S., Konrad, C., Pantev, C., & Huster, R. J. (2010). Conflict and inhibition differentially affect the N200/P300 complex in a combined go/nogo and stop-signal task. *NeuroImage*, *51*(2), 877–887. https://doi.org/10.1016/j.neuroimage.2010.02.043

Filevich, E., Kühn, S., & Haggard, P. (2012). Intentional inhibition in human action: The power of "no." *Neuroscience and Biobehavioral Reviews*, *36*(4), 1107–1118. https://doi.org/10.1016/j.neubiorev.2012.01.006

Ghosh, A., Rothwell, J., & Haggard, P. (2014). Using voluntary motor commands to inhibit involuntary arm movements. *Proceedings of the Royal Society B: Biological Sciences*, *281*(1794). https://doi.org/10.1098/rspb.2014.1139

Greenhouse, I., & Wessel, J. R. (2013). EEG signatures associated with stopping are sensitive to preparation. *Psychophysiology*, *50*(9), 900–908. https://doi.org/10.1111/psyp.12070

Groom, M. J., & Cragg, L. (2015). Differential modulation of the N2 and P3 event-

related potentials by response conflict and inhibition. *Brain and Cognition*, *97*, 1–9. https://doi.org/10.1016/j.bandc.2015.04.004

Gruber, M. J., Watrous, A. J., Ekstrom, A. D., Ranganath, C., & Otten, L. J. (2013). Expected reward modulates encoding-related theta activity before an event. *NeuroImage*, *64*(1), 68–74. https://doi.org/10.1016/j.neuroimage.2012.07.064

Hajihosseini, A., & Holroyd, C. B. (2013). Frontal midline theta and N200 amplitude reflect complementary information about expectancy and outcome evaluation. *Psychophysiology*, *50*(6), 550–562. https://doi.org/10.1111/psyp.12040

Heilbronner, S. R., & Hayden, B. Y. (2016). Dorsal Anterior Cingulate Cortex: A Bottom-Up View. *Annual Review of Neuroscience*, *39*(1), 149–170. https://doi.org/10.1146/annurev-neuro-070815-013952

Hwang, E. J. (2013). The basal ganglia, the ideal machinery for the cost-benefit analysis of action plans. *Frontiers in Neural Circuits*, *7*(July), 1–6. https://doi.org/10.3389/fncir.2013.00121

Kawasaki, M., & Yamaguchi, Y. (2013). Frontal theta and beta synchronizations for monetary reward increase visual working memory capacity. *Social Cognitive and Affective Neuroscience*, *8*(5), 523–530. https://doi.org/10.1093/scan/nss027

Kayser, J., & Tenke, C. E. (2006). Principal components analysis of Laplacian waveforms as a generic method for identifying ERP generator patterns: I. Evaluation with auditory oddball tasks. *Clinical Neurophysiology*, *117*(2), 348–368. https://doi.org/10.1016/j.clinph.2005.08.034

Klein-Flugge, M. C., Kennerley, S. W., Friston, K., & Bestmann, S. (2016). Neural Signatures of Value Comparison in Human Cingulate Cortex during Decisions Requiring an Effort-Reward Trade-off. *Journal of Neuroscience*, *36*(39), 10002–10015. https://doi.org/10.1523/JNEUROSCI.0292-16.2016

Kok, A., Ramautar, J. R., De Ruiter, M. B., Band, G. P. H., & Ridderinkhof, K. R. (2004). ERP components associated with successful and unsuccessful stopping in a stop-signal task. *Psychophysiology*, *41*(1), 9–20. https://doi.org/10.1046/j.1469-8986.2003.00127.x

Krämer, U. M., Knight, R. T., & Münte, T. F. (2011). Electrophysiological Evidence for Different Inhibitory Mechanisms When Stopping or Changing a Planned Response. *Journal of Cognitive Neuroscience*, *23*(9), 2481–2493. https://doi.org/10.1162/jocn.2010.21573

Kühn, S., Haggard, P., & Brass, M. (2009). Intentional inhibition: How the "veto-area" exerts control. *Human Brain Mapping*, *30*(9), 2834–2843. https://doi.org/10.1002/hbm.20711

Liebrand, M., Pein, I., Tzvi, E., & Krämer, U. M. (2017). Temporal Dynamics of Proactive and Reactive Motor Inhibition. *Frontiers in Human Neuroscience*, *11*(April), 1–14. https://doi.org/10.3389/fnhum.2017.00204

Logan, G. D., & Cowan, W. B. (1984). On the ability to inhibit thought and action: A theory of an act of control. *Psychological Review*, *91*(3), 295–327. https://doi.org/10.1037/0033-295X.91.3.295

Manohar, S. G., & Husain, M. (2016). Human ventromedial prefrontal lesions alter incentivisation by reward. *Cortex*, *76*, 104–120. https://doi.org/10.1016/j.cortex.2016.01.005

Marcos, E., Cos, I., Girard, B., & Verschure, P. F. M. J. (2015). Motor cost influences perceptual decisions. *PLoS ONE*, *10*(12), 1–12. https://doi.org/10.1371/journal.pone.0144841

Michaels, J. A., Dann, B., Intveld, R. W., & Scherberger, H. (2015). Predicting Reaction Time from the Neural State Space of the Premotor and Parietal Grasping Network. *Journal of Neuroscience*, *35*(32), 11415–11432. https://doi.org/10.1523/JNEUROSCI.1714-15.2015

Ramautar, J. R., Kok, A., & Ridderinkhof, K. R. (2006). Effects of stop-signal modality on the N2/P3 complex elicited in the stop-signal paradigm. *Biological Psychology*, *72*(1), 96–109. https://doi.org/10.1016/j.biopsycho.2005.08.001

Rangel-Gomez, M., Knight, R. T., & Krämer, U. M. (2015). How to stop or change a motor response: Laplacian and independent component analysis approach. *International Journal of Psychophysiology*, *97*(3), 233–244. https://doi.org/10.1016/j.ijpsycho.2015.01.012

Schevernels, H., Bombeke, K., Van der Borght, L., Hopf, J. M., Krebs, R. M., & Boehler, C. N. (2015). Electrophysiological evidence for the involvement of proactive and reactive control in a rewarded stop-signal task. *NeuroImage*, *121*, 115–125. https://doi.org/10.1016/j.neuroimage.2015.07.023

Schweighofer, N., Xiao, Y., Kim, S., Yoshioka, T., Gordon, J., & Osu, R. (2015). Effort, success, and nonuse determine arm choice. *Journal of Neurophysiology*, *114*(1), 551–559. https://doi.org/10.1152/jn.00593.2014

Seitz, R. J., Franz, M., & Azari, N. P. (2009). Value judgments and self-control of action: The role of the medial frontal cortex. *Brain Research Reviews*, *60*(2), 368–378. https://doi.org/10.1016/j.brainresrev.2009.02.003

Shadmehr, R., Huang, H. J., & Ahmed, A. A. (2016). A Representation of Effort in Decision-Making and Motor Control. *Current Biology*, *26*(14), 1929–1934. https://doi.org/10.1016/j.cub.2016.05.065

Shenhav, A., Botvinick, M. M., & Cohen, J. D. (2013). The expected value of control: An integrative theory of anterior cingulate cortex function. *Neuron*, *79*(2), 217–240. https://doi.org/10.1016/j.neuron.2013.07.007

Van Noordt, S. J. R., Campopiano, A., & Segalowitz, S. J. (2016). A functional classification of medial frontal negativity ERPs: Theta oscillations and single subject effects. *Psychophysiology*, *53*(9), 1317–1334. https://doi.org/10.1111/psyp.12689

van Noordt, S. J. R., Desjardins, J. A., & Segalowitz, S. J. (2015). Watch out! Medial frontal cortex is activated by cues signaling potential changes in response demands. *NeuroImage*, *114*, 356–370. https://doi.org/10.1016/j.neuroimage.2015.04.021

Verleger, R., Paehge, T., Kolev, V., Yordanova, J., & Jaśkowski, P. (2006). On the relation of movement-related potentials to the go/no-go effect on P3. *Biological Psychology*, *73*(3), 298–313. https://doi.org/10.1016/j.biopsycho.2006.05.005

Zandbelt, B. B., & Vink, M. (2010). On the role of the striatum in response inhibition. *PLoS ONE*, *5*(11). https://doi.org/10.1371/journal.pone.0013848

Zavala, B. A., Tan, H., Little, S., Ashkan, K., Hariz, M., Foltynie, T., … Brown, P. (2014). Midline Frontal Cortex Low-Frequency Activity Drives Subthalamic Nucleus Oscillations during Conflict. *Journal of Neuroscience*, *34*(21), 7322–7333. https://doi.org/10.1523/JNEUROSCI.1169-14.2014

APPENDIX A

TABLES F0R SUMMARY STATISTICS

Regression with quadratic fit across subjects at P(stop)=0.15				
	ß	SE ß	*t*	*p*
Intercept	0.317	0.023	13.723	<2e-16
Reaction time (m/s/s)	-1.104	0.131	-8.451	<2e-16
Reaction time squared (m/s/s^2)	2.873	0.128	16.139	<2e-16
Block	-0.004	0.002	-2.334	0.0198

Table 1. Regression table for peak reach velocity against reaction time during successful Go trials.

Observed probability of inhibition				
	Without effort (Block 2)		With effort (Block 3)	
P(stop)	mean	se	mean	se
0.15	0.086	0.03	0.041	0.02
0.4	0.290	0.05	0.265	0.06
0.6	0.567	0.07	0.706	0.06
0.85	0.879	0.04	0.933	0.02

Table 2. Mean probability of inhibition computed from raw experimental data.

Predicted probability of inhibition				
	Without effort (Block 2)		With effort (Block 3)	
-P(stop)	mean	se	mean	se
0.15	0.086	0.02	0.036	0.01
0.4	0.278	0.03	0.253	0.03
0.6	0.578	0.04	0.715	0.03
0.85	0.891	0.02	0.940	0.01

Table 3. Mean probability of inhibition predicted from generalized linear mixed effect model.

Reaction time (ms)						
	Go trials only (Block 1)		Go and Stop trials (Block 2)		Go and Stop trials with effort (Block 3)	
P(stop)	mean	se	mean	se	mean	se
0	265.73	29.43	-	-	-	-
0.15	-	-	386.42	20.04	360.91	21.90
0.4	-	-	393.75	19.00	389.99	20.01
0.6	-	-	404.65	21.81	389.20	22.00
0.85	-	-	385.63	46.03	377.29	27.24

Table 4. Mean reaction time computed from raw experimental data.

Regression with quadratic fit across subjects					
		ß	SE ß	*t*	*p*
Block 2 (Without effort)	Intercept	0.262	0.0441	5.930	1.08e-8
	Reaction time (m/s/s)	-7.59e-4	2.38e-4	-3.194	0.0016
	Reaction time squared ($m/s/s^2$)	2.34e-6	3.11e-7	7.538	1.05e-12
		ß	SE ß	*t*	*p*
Block 3 (With effort)	Intercept	0.348	0.0274	12.700	<2e-16
	Reaction time (m/s/s)	-1.29e-3	1.59e-4	-8.115	2.88e-15
	Reaction time squared ($m/s/s^2$)	3.16e-6	2.20e-7	14.377	<2e-16

Table 5. Regression over each block separately on successful Go trials at P(stop)=0.15 condition

Theta band (4-8Hz)						
		df	*SS*	*MS*	*F*	*p*
Post-BarOn	Stop probability	3	1.06	0.352	0.206	0.892
	Block	1	1.56	1.662	0.915	0.341
	Stop probability and block	3	0.28	0.093	0.055	0.983
	total	88	150.12	1.706	-	-
		df	*SS*	*MS*	*F*	*p*
Post-BarStart	Stop probability	3	8.29	2.762	1.005	0.394
	Block	1	0.62	0.622	0.226	0.635
	Stop probability and block	3	1.86	0.622	0.226	0.878
	total	88	241.77	2.747	-	-

Table 6. ANOVA table for theta band during motor preparatory period.

Alpha band (9-12Hz)						
	factor	*df*	*SS*	*MS*	*F*	*p*
Post-BarOn	Stop probability	3	2.35	0.783	0.319	0.812
	Block	1	0.22	0.219	0.089	0.766
	Stop probability and block	3	1.01	0.338	0.138	0.937
	total	88	216.00	2.455		
		df	*SS*	*MS*	*F*	*p*
Post-BarStart	Stop probability	3	5.85	1.949	0.885	0.452
	Block	1	4.12	4.119	1.871	0.175
	Stop probability and block	3	2.28	0.759	0.345	0.793
	total	88	193.77	2.202		

Table 7. ANOVA table for alpha band during motor preparatory period.

APPENDIX B

SIGNED CONSENT FORMS

identity cannot be determined from any of the data. The key to the code is kept in a separate location from the data and the data are locked in a cabinet. Only Marco Santello or Justin Fine and the research assistant that enrolled you in the study will have access to both the codes and the code key.

WITHDRAWAL PRIVILEGE

It is ok for you to say no. Even if you say yes now, you are free to say no later, and withdraw from the study at any time. Your decision will not affect your relationship with Arizona State University or otherwise cause a loss of benefits to which you might otherwise be entitled.

COSTS AND PAYMENTS

The researchers want your decision about participating in the study to be absolutely voluntary. Yet they recognize that your participation may pose some inconvenience. You will be paid $20 for each session. All payments are made at the end of each phase.

COMPENSATION FOR ILLNESS AND INJURY

If you agree to participate in the study, then your consent does not waive any of your legal rights. However, no funds have been set aside to compensate you in the event of injury.

VOLUNTARY CONSENT

Any questions you have concerning the research study or your participation in the study, before or after your consent, will be answered by one of the following people: Dr. Marco Santello (480-965-8279), Justin Fine (480-965-8279), or Qiushi Fu (480-965-8279).

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Your signature below indicates that you consent to participate in the above study.

Subject's Signature	Printed Name	Date
	Sonya Shen	12/12/17

INVESTIGATOR'S STATEMENT

"I certify that I have explained to the above individual the nature and purpose, the potential benefits and possible risks associated with participation in this research study, have answered any questions that have been raised, and have witnessed the above signature. These elements of Informed Consent conform to the Assurance given by Arizona State University to the Office for Human Research Protections to protect the rights of human subjects. I have provided (offered) the subject/participant a copy of this signed consent document."

Signature of Investigator _____ Date 12/12/17

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Subject's Signature	Printed Name	Date
Kaeru	Kaoru Kato	12/13/2017

INVESTIGATOR'S STATEMENT

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Signature of Investigator _____ Date 12/13/17

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Subject's Signature	Printed Name	Date
Shinji Otsuru	Shinji Otsuru	12/15/17

INVESTIGATOR'S STATEMENT

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Signature of Investigator _____ Date 12/15/17

VOLUNTARY CONSENT

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Subject's Signature	Printed Name	Date
	Yen-Hsun Wu	1/30/2018

INVESTIGATOR'S STATEMENT

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Signature of Investigator _____ Date 1/30/18

VOLUNTARY CONSENT

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Your signature below indicates that you consent to participate in the above study.

Subject's Signature	Printed Name	Date
	Andrew Lavitsky	2/2/18

INVESTIGATOR'S STATEMENT

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Signature of Investigator _____ Date 4/2/18

VOLUNTARY CONSENT

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Subject's Signature	Printed Name	Date
	Peiyuan Wang	2.6.2018

INVESTIGATOR'S STATEMENT

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Signature of Investigator _____ Date 2/6/18

VOLUNTARY CONSENT

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Your signature below indicates that you consent to participate in the above study.

Subject's Signature	Printed Name	Date
Kohei Ito	Kohei Ito	2/7/2018

INVESTIGATOR'S STATEMENT

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Signature of Investigator _____ Date 2/7/18

VOLUNTARY CONSENT

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Your signature below indicates that you consent to participate in the above study.

Ryo Morishima — Subject's Signature

Ryo Morishima — Printed Name

2/8/2018 — Date

INVESTIGATOR'S STATEMENT

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Signature of Investigator _____ Date 2/8/18

VOLUNTARY CONSENT

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Subject's Signature	Printed Name	Date
Kaycee Glatfke	Kaycee Glatfke	2/9/18

INVESTIGATOR'S STATEMENT

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Signature of Investigator _____ Date 2/9/18

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Hironobu Nihei — Hironobu Nihei — Feb. 15. 2018

Subject's Signature | Printed Name | Date

INVESTIGATOR'S STATEMENT

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Signature of Investigator _____ Date 2/15/18

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Subject's Signature	Jakob Wells Printed Name	2/20/18 Date

INVESTIGATOR'S STATEMENT

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Signature of Investigator _____ Date 2/20/18

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Subject's Signature	Printed Name	Date
	LIVIA DE MESQUITA FERREIRA	02/21/2018

INVESTIGATOR'S STATEMENT

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Signature of Investigator _____ Date 2/21/2018

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Akiro Hibino	Akiro Hibino	2/23 2018
Subject's Signature	Printed Name	Date

INVESTIGATOR'S STATEMENT

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Signature of Investigator _____ Date 2/23/18

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Subject's Signature	Printed Name	Date
Scott Boege	Scott Boege	1/25/18

INVESTIGATOR'S STATEMENT

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Signature of Investigator _____ Date 1/25/18

VOLUNTARY CONSENT

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Subject's Signature	Printed Name	Date
	FRANCISCO LOPEZ	Jan 26 2018

INVESTIGATOR'S STATEMENT

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Signature of Investigator _____ Date 1/26/2018

VOLUNTARY CONSENT

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Your signature below indicates that you consent to participate in the above study.

Subject's Signature	Printed Name	Date
[signature]	Jacob Perrin	2/28/18

INVESTIGATOR'S STATEMENT

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Signature of Investigator [signature] Date 2/28/18