UNIVERSITY OF PADOVA

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Master's Degree in Cognitive Neuroscience and Clinical Neuropsychology

Final dissertation

The Role of Inhibition and its Neural Substrate in Decision-Making: A Transcranial Magnetic Stimulation Study

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"Scientists try to eliminate their false theories, they try to let them die in their stead. The believer – whether animal or man – perishes with his false beliefs." (Popper, 1968)

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Abstract

A vital aspect of daily life in our uncertain world is to make decisions, which are often accompanied by the capacity to inhibit those that are inadequate. Inhibition supports this process by controlling our main responses and suppressing irrelevant information that interferes with decision-making (DM). There are three main cortical brain areas involved in DM: The right inferior frontal gyrus (rIFG), the pre-supplementary motor area (pre-SMA), and the primary motor cortex (M1). However, it is unclear which of the various pathways linking these regions and the subcortical areas involved are crucial for inhibitory control. Thus, the present research aimed to investigate the causality of the brain areas involved in this network using continuous theta burst stimulation (cTBS) in healthy participants. A total of 17 healthy individuals (11 females) with a mean age of M = 25.12 (SD = 4.40), ranging from 20 to 35 years, underwent three randomized sessions of cTBS applied over rIFG, pre-SMA, and sham stimulation to the vertex. Participants completed the TMS health and safety checklist before each session and a series of questionnaires (e.g., STAI, Barratt BIS-11, etc.). Before receiving the cTBS condition, subjects performed a stop-signal task and after the stimulation, they completed the two versions of a multiattribute probabilistic inference task in a counterbalanced order (PIT; compensatory [C] and noncompensatory [NC] task structure). The preliminary results indicate that regardless of the structure of the task, the heuristic Take-the-Best (TTB) was a better strategy than the weighted additive rule (WADD) for describing the inferences of the participants. Regarding the effects of cTBS, inhibiting rIFG did not produce any significant effect on participants' relative strategy preference (RSP) compared to sham. On the contrary, inhibiting pre-SMA led to a significant decrease in the RSP of TBB over WADD in the block trial where the proportion of discriminatory trials was the highest. Although our study lacks the power analysis needed to draw reliable conclusions, the

results suggest that the rIFG may function as a hub that hosts functional networks other than only inhibition, while the effects of inhibiting pre-SMA may indicate that it functions as a modulatory center of decision thresholds. More studies are needed in the convergence of multiattribute decision-making with TMS to better understand the causal role of the cortical and subcortical areas involved in inhibitory control.

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1. Chapter 1: Decision-Making

1.1. Cognitive Control, Inhibition, and Decision-Making

Numerous situations in daily life trigger automatic behaviors and cognitive processes in response to stimuli around us (i.e., our environment). Cognitive control (CC), also referred to as "executive function" (Aron, 2007), allows us to adjust our chain of thoughts and behaviors away from those elicited automatically, enabling us as humans to execute greater cognitive processes such as reasoning, planning, inhibiting, and retaining and managing information in our working memory (Kool et al., 2017). It comprises choosing actions that are aligned with our current goals and context (Badre, 2008). Namely, this adjustment is made following our intentions, goals, and values (Steinbeis & Crone, 2016) and includes various mental operations. For example, the representation of current objectives (goals), focusing our attention on crucial environmental factors to achieve such goals, and carrying out actions and behaviors consistent with them in diverse contexts (Botvinick & Braver, 2015). In terms of its function in decision making, cognitive control is essential to recall what the objective is (e.g., to buy a flat), to shift attention to features of a current goal (e.g., ignoring big and unnecessary expenses such as buying a newer car), and to implement a strategy for achieving the goal (e.g., budgeting; Steinbeis & Crone, 2016).

One of the higher cognitive processes enabled by cognitive control, inhibition, can have many connotations, ranging from connections between brain regions to systems or mechanisms controlling behavioral output, to cellular firing, and more. In this master's thesis, inhibition will be understood as "the suppression of inappropriate responses, stimulus-response mappings or task-sets when the context changes, and suppression of interfering memories during retrieval." (Aron et al., 2014, p. 177; Aron et al., 2004).

Inhibitory control has been widely studied as a two-fold process (Tiego et al., 2018): (1) Response Inhibition [also known as "Behavioral Inhibition", "Motor Inhibition", "Prepotent Response Inhibition", and "(Attention) Restraint"], and (2) Attentional Inhibition [also known as "Interference Control", "Interference Suppression", "Resistance to (Distracter) Interference", and "Attention Constraint"] (Friedman & Miyake, 2004; Kane et al., 2016; Nigg, 2000; Nigg, 2017; Stahl et al., 2014; Wiebe et al., 2008; Xu et al., 2020). Motor response inhibition refers to the ability to intentionally withhold or cancel motor actions, whether they are habitual, initialized, or pre-potent responses (Hampshire, 2015). Attentional inhibition refers to the ability to withstand interference from external environmental stimuli (Tiego et al., 2018). Inhibition is a crucial function in decision-making, as it helps in the process of deciding between potential alternative responses (Moeller et al., 2001) and helps to improve it, that is, people must continuously manage their dominant responses (response inhibition) and irrelevant interference information (attentional inhibition; Xu et al., 2020).

1.2. Decision-Making

The cognitive ability to make decisions is a fundamental part of daily living and is required for autonomy and environmental adaptation (Morelli et al., 2021). It is a nuanced executive function derived from prior experience, current objectives, and anticipation of results, shaped by current and predicted emotions and culture (Rosenbloom et al., 2012). To arrive at a decision, that is, to make a choice, the mind can apply logic, statistics, or heuristics. The first two have been linked to rational reasoning, whereas heuristics have been linked to irrational thinking or intuitions susceptible to committing errors (Tversky & Kahneman, 1974; Kahneman, 2003). However, other lines of research understand heuristics as simple rules that can enable us to make smart choices with limited time and information by exploiting the way this information is structured in specific environments

(Gigerenzer et al., 1999; Todd & Gigerenzer, 2000). Despite the variety of literature on decision-making, we can recognize two main theoretical frameworks: normative theories and descriptive theories. The foremost is based on the Expected Utility Theory (Von Neumann & Morgenstern, 1944), which follows a group of statements known as axioms, namely, transitivity, cancellation, dominance, and invariance. These axioms describe different conditions in which an individual's choice under uncertainty is guided by maximizing the gains while maintaining the loss to the minimum. In other words, in situations of uncertainty, individuals make decisions by considering the expected utility of the options to choose. That is, every action has an expected outcome (i.e., a foreseen consequence), and for each possible outcome a value that represents the probability (or expected utility) of that outcome happening is allocated (Morelli et al., 2022). Then, the option that yields the highest benefit and minimum loss is selected. When an individual's choice adheres to the axioms, it is considered a rational decision, since the rational agent now makes a decision following logic or statistics. However, people's choices often violate these axioms, leading to "irrational" decisions. For this reason, descriptive theories recognize that our mind does not work exclusively with rational reasoning, but we often choose, consciously or not, shortcuts or heuristics to decide the course of our actions. In this research, a heuristic will be understood as a "strategy that ignores part of the information, with the goal of making decisions more quickly, frugally, and/or accurately than more complex methods [and to reduce the effort required to make a decision]" (Gigerenzer & Gaissmaier, 2011, p. 454). A strategy, a term rooted in game theory, is a list of individual rules that stipulate what your move will be for every plausible previous set of moves for the specific game you are playing (Edwards, 1954; Weiss & Weiss, 2009).

Ward Edwards provided an extended review of the literature on decision-making

since 1930 (Edwards, 1954, 1968; Edwards et al., 1963). Our idea is not to recall all historical events on this topic, but to raise the idea that his research certainly pushed forward the vision of an "economic individual" and its rationality in the field of psychology. According to him, an economic individual can be seen as unboundedly rational, with no limits in terms of cognition and time, who makes his choices to maximize something (Edwards, 1954). Edwards understood how we update our beliefs or calculate posterior probabilities based on new evidence (the Bayes' theorem: a mathematical formula that calculates the probability of an event based on prior information or knowledge) and how this applies to cognitive tasks. Although these ideas were aligned with normative theories, Edwards and his colleagues also discovered that our decisions often deviate from normative rules. As a result, they established a fundamental framework for the study of the psychology of decision-making: first, utilize normative decision theory to explain rational behavior, then assess actual behavior against the norms, and last, infer the reasons behind deviations (Clemen & Kleinmuntz, 2005).

In parallel, Herbert A. Simon (1955), the "father" of the theory of bounded rationality and a descriptive theorist of decision-making, held a view in which he saw two intertwined elements: the limitations of the human mind, and the structure of the environment in which the mind operates (Gigerenzer & Todd, 1999). Although Simon's theory dates back to 1955 he continued to present it and describe it in more detail in subsequent publications (Simon, 1956a, 1979a, 1979b, 1990). Regarding the limitations of the human mind, Simon proposed that our psychological characteristics, such as our computational and predictive abilities, are limited. He suggested that human rationality can, at best, be a simplified approximation to the type of global rationality described in normative theories. As Simon (1990) stated, the most important law that holds both to computers and human brains is that "their rationality is bounded" (p. 6). In other words,

the main difference between unbounded and bounded rationality is that the former assumes that information search can continue endlessly, and therefore unbounded models of decision-making aim at finding an optimal solution to a problem or situation. In contrast, bounded rationality models include a limited information search, because decision-makers have a restricted amount of time, knowledge, cognitive resources, or even money to allocate to a specific decision. Due to these constraints, which often happen in real-world situations, the optimal solution is unreachable, as there is no guarantee that the chosen strategy is optimal. In essence, the optimal strategy is unforeseeable (Hoffrage, 2014; Simon, 2008). Furthermore, for the information to be limited, the search has to have an end, that is, a method or stopping rule for determining when to cease exploring for information is necessary for a limited search (Gigerenzer & Todd, 1999).

Following Simon's perspective, models of bounded rationality encompass what he called "satisficing" and "fast and frugal" heuristics. Satisficing is a process of choosing a satisfactory solution from a collection of options presented sequentially when one is unsure of the alternatives ahead of time (Gigerenzer & Todd, 1999). The level of criteria that defines "satisfactory" for each individual follows a psychological mechanism of aspiration level: The decision maker raises or lowers the level depending on whether is too easy or it takes too long to find alternatives that meet the criteria, respectively (Simon, 2008). Yet, when an alternative exceeds the aspirated level, the search for an option concludes (the satisficing option was found; Simon, 1956a, 1990). However, to set an adequate aspiration level from the beginning or determine how a current option relates to the aspiration level, the decision maker may still need considerable time or cognitive resources (even if all information is available) to consider any of these options (Simon, 1956b). For this reason, "fast and frugal" heuristics are useful in these circumstances

because they require a minimum of time, knowledge, and cognitive resources to make adaptive choices in real-world situations (Gigerenzer & Todd, 1999). These heuristics are fast because they do not incorporate or combine the attained information in a time-consuming way, but the decision is based on one single reason. They are frugal because they stop looking for information at an early stage of the process of obtaining information, so they search for some of the existing information (Hoffrage, 2014).

The other element of Simon's view, the environmental structure, is a concept that other authors used in psychology and probability before his theory (e.g., Brunswik, 1943). If we look at the environmental structure in which the mind operates, we can explain when and why simple heuristics perform well as long as the heuristic structure is adjusted to that of the environment (Gigerenzer & Todd, 1999). An environment is a set of objects (options) that are characterized by a criterion value and a cue profile (Martignon & Hoffrage, 1999). Let us imagine that an individual received four job offers. These represent the set of objects, that is, the options available among which the decision maker can choose. If the job offers are ranked following the salary criterion, then each one of them will have a cue profile given by the cues that the individual identifies such as the benefits, work-life balance, company culture, career growth prospects, etc.

Gigerenzer & Todd (1999) introduced the term "ecological rationality" to re-introduce the importance of the environmental structure in bounded rationality. This term can be unfolded in two parts. First, the effectiveness of a heuristic is evaluated against an environmental criterion (i.e., the ecology) rather than against a probabilistic or logical norm (Hoffrage, 2014). This suggests that most fast and frugal heuristics have been developed to conclude about objective states of the environment, rather than creating subjective preferences that reflect an individual's utilities. Second, a heuristic's success

and ecological rationality can be encountered in "the fit between the structural properties of the heuristic and the structure of the environment it is applied to" (Martignon & Hoffrage, 1999, p.119-120). Then, we can note that both the heuristics and the environment have a structure composed of building blocks. Although heuristics differ from each other, they all share the same building blocks (structure), also referred to as principles. These are: how information is searched for (principle of search), when information search is terminated (principle of stopping), and how a decision is made based on the information attained (principle of decision) [Hoffrage, 2014; Rieskamp & Hoffrage, 1999]. These three can then be used to characterize any specific strategy. Within the structure of a decision, we can recognize the options or alternatives, each characterized by a cue (or attribute) values, their potential results or consequences, and the conditional probabilities or weights (or validity) that link the options with their results (Rieskamp & Hoffrage, 1999; Tversky & Kahneman, 1985).

From the perspective of ecological rationality, peoples' mind is equipped with an "adaptive toolbox" which contains several strategies (i.e., searching, stopping, and decision rules), and these can be used adaptively in response to different environmental structures (Rieskamp & Hoffrage, 1999; Todd & Gigerenzer, 2012). These environmental structures can be of two classes: noncompensatory and compensatory (Martignon & Hoffrage, 1999, 2002). In a noncompensatory environment, the most important cues or attributes cannot be outweighed by any combination of less significant cues. Formally, Martignon and Hoffrage define it as an ordered set of M binary cues, $C_1, \dots C_M$, in which every cue C_j outweighs any possible combination of cues after C_j, that is, C_{j+1} to C_M. Similarly, the same is true in the specific situation of weighted linear models if, for a given ordering of the weights, each weight is greater than the total of all weights that will follow. A common example is the set {1, 1/2, 1/4, 1/8, 1/16}. On the contrary, in a

compensatory environment, one or more cues can be outweighed (compensated for) by a combination of less important cues.

1.2.1. Decision-Making Theories and Heuristics Taxonomy

The taxonomy of heuristics is an ongoing project in cognitive psychology, and there has not yet been a general agreement on this. Different researchers and their lines of research in decision-making propose their taxonomies based on their theoretical framework and empirical findings. One of the well-established models of human decision-making is the dual-system theory or dual-process theory (Evans & Stanovich, 2013; Kahneman, 2003; Kahneman & Frederick, 2002; Stanovich, 1999; Stanovich & West, 2002; Wason & Evans, 1975). Although Daniel Kahneman made the dual-system theory accessible to individuals outside the sphere of psychology (Kahneman, 2011), there are some differences between the subtypes of this model (Evans & Stanovich 2013). However, what is shared across all accounts of dual-system theories is that our cognitive processes can be understood in a two-fold way. System 1 is used to describe automatic, effortless, rapid, and associative thinking, and System 2 represents controlled, effortful, slower, and deductive thinking. In other words, these systems are distinguished by their speed, controllability, and the contents on which they operate. In the proposed model by Kahneman & Frederick (2002), System 1 is responsible for providing intuitive answers to judgment problems as they appear, and System 2 monitors the quality of these answers, which it may approve, amend, or reject. Under this framework, heuristics are associated with System 1, to our intuitive judgment, and are used to assess probabilities and predict values (Tversky & Kahneman, 1974). These heuristics, namely, representativeness, availability and, adjustment and anchoring, are advantageous to simplify complex cognitive tasks but sometimes they manifest or lead to severe and systematic errors (i.e., biases).

The terms “ecological rationality”, “adaptive toolbox”, and the idea that heuristics have a structure composed of building blocks, among others, that were described earlier are part of the framework of decision-making of Gigerenzer and colleagues (1999). Unlike the dual-system theory that relates heuristics to System 1 (unconscious, associative, error-prone processes), their approach considers heuristics relying upon both unconscious and conscious processes, which are defined as a rule. Further, the amount of error resulting from heuristics can be measured and contrasted with those of other strategies (Gigerenzer & Gaissmaier, 2011). Their theoretical framework focuses on going beyond a list of heuristics by grouping them according to their building blocks, leading to a classification based on how they are constructed. The main categories of heuristics listed by Gigerenzer & Gaissmaier (2011) are recognition-based decision-making, one-reason decision-making, and trade-off heuristics. This project pays particular attention to the first two categories, especially the Recognition heuristic (RH), which belongs to the first group, and the Take-the-best heuristic (TTB) part of the second group.

Our interest in the RH relies on the fact that is closely connected with the TTB heuristic. To understand how the former works, a simple example is provided. When twelve U.S. and German citizens were asked if San Diego or San Antonio had a larger population, about two-thirds of the U.S. citizens accurately answered that San Diego is larger (Goldstein & Gigerenzer, 2002). However, despite the assumption that Germans may lack knowledge of U.S. geography or its distribution of population, 100% of the Germans answered the question correctly. Although this seems to be an error, the RH describes these decision-making scenarios. What happened is that Germans that were tested had heard of San Diego but half of them did not recognize San Antonio, which led them to infer that San Diego is larger. In other words, Germans used the fact that they did

not recognize San Antonio as the basis for their predictions. This strategy is known as the recognition heuristic (RH). For two-alternative choice tasks, the RH is defined as: "if one of two objects is recognized and the other is not, then infer that the recognized object has the higher value with respect to the criterion" (Goldstein & Gigerenzer, 2002, p.76). This means that the RH aims to conclude (infer) about a criterion that is not immediately available to the decision maker, but it is based on familiarity, that is, memory-retrieved recognition (Gigerenzer & Gaissmaier, 2011). According to research on this last subject, consciousness first experiences familiarity, a sense of recognition that does not cue any associative information, before recollection which prompts a variety of contextual, temporal, and other associative information from memory (Carlesimo et al., 2015; Ratcliff & McKoon, 1989). The RH is useful when there is a positive or negative strong correlation between recognition and criterion (Goldstein & Gigerenzer, 2002).

If the scenario changes and both objects are recognized in a two-alternative choice task, then the RH does not discriminate between them (Hoffrage, 2014). In these cases, the one-reason decision-making TTB can be used. This heuristic is a lexicographic strategy that is based on the principle of satisficing, meaning that its goal is to find a satisfactory solution rather than an optimal one. It is lexicographic because cues are searched in a fixed order of validity, first searches for the cue with the highest validity, and if it does not discriminate, it moves to the next best cue, and so on (Gigerenzer & Goldstein, 1999). When using TTB, individuals infer using binary cue values recalled from memory, leading to choosing the option that has a higher value on a criterion (Gigerenzer & Gaissmaier, 2011). However, while that decision may be wrong, none of the other cues or combinations of them will change it. In other words, TTB is a noncompensatory strategy (Martignon & Hoffrage, 2002). The following building blocks make up Take-the-Best (Gigerenzer & Gaissmaier, 2011; Hoffrage, 2014): (a)

Recognition heuristic; (b) Search rule: If both options are recognized, search and choose the cue with the highest validity (search through cues in order of their validity); (c) Stopping rule: If the cue values are 1 and 0 stop when finding the first cue that discriminates between the alternatives. If the option has a positive value and the other does not (i.e., has either a negative or unknown value), then stop the search and go on to the next step. If not go back to the previous step and search for another cue; (d) Decision rule: Infer that the alternative with the positive cue value hast the higher value on the criterion.

Another decision-making strategy that belongs to the group of normative theories (as opposed to TTB which is a descriptive heuristic) is the weighted additive rule (WADD) also known as Franklin's moral algebra or Franklin's rule (Payne et al., 1993). This rule is categorized as compensatory as it allows to offset (i.e., compensate) low values in one attribute by considering high values on other attributes (Dawes & Corrigan, 1974). It is a linear model that is considered one of the traditional gold standards for rational judgment under uncertainty (Gigerenzer & Goldstein, 1999). WADD takes into account all values of each option on all of the relevant attributes (outcomes) and all of the relative weights (probabilities) of the different attributes (outcomes) to the individual (Payne et al., 1985). The strategy builds a weighted value for each attribute by multiplying its weight (probability) by its value and sums over all attributes to arrive at a general evaluation of an alternative, selecting as a result the option with the highest calculation. The importance of using WADD relies on the fact that is widely used in research as a criterion for decision effectiveness in multiattribute choice (Beach et al., 1986; see also Beach & Mitchell, 1978; Zakay & Wooler, 1984). Further, the research of Payne and his colleagues (Payne et al., 1985; Payne et al., 1992; Payne et al., 1993) employ WADD as a gold standard, in which they define accuracy in terms of how close a strategy

approximates WADD. Therefore, no strategy can ever be more accurate than the norm (an exception is when WADD is changed to use only limited information; Gigerenzer & Goldstein, 1999). However, as mentioned earlier, in real-world situations with enough complexity, knowledge, time, and computation required to perform the traditional ideal of unbounded rationality (such as WADD) cannot be possible due to our cognitive limitations. Thus, when making inferences in these scenarios, the WADD strategy is not necessarily the one that performs the best (Gigerenzer & Goldstein, 1999).

The theory on what strategies from the "adaptive toolbox" individuals often use points out that lexicographical models (e.g., TTB) on binary cues generate the same performance as linear models (e.g., WADD) with noncompensatory weights (Martignon & Hoffrage, 1999, 2002). Further, as usually the skewness of our environment (i.e., the world around us) is noncompensatory, TTB and even more complex linear models yield equal performances when making inferences. However, certain (extreme) environments intensify disparities: TTB is favored under scarce environments, while abundant information favors WADD (Martignon & Hoffrage, 1999). This theoretical view is consistent with empirical findings obtained by Payne and colleagues (1988, 1993), who found that individuals choose their strategies depending on the conditions imposed on them by the environment. These findings are the foundation of the adaptive decision-maker hypothesis. This hypothesis holds that the selection of strategies is adaptive to the structure of the environment, that is to say, the individual will choose strategies that are relatively efficient in terms of effort and accuracy in ways that this strategy is appropriate given the subtle changes in the structure of the decision problem (environment) they face (Payne et al., 1988). Moreover, decision-makers also respond highly adaptatively to the presence of time pressure. In this last scenario, their research supports a three-folded perspective that works in a cascade. First, people may attempt to accelerate their

processing and try to employ the chosen strategy faster. Second, if this approach is not enough due to the large time constraint, individuals may next just focus on a portion of the available information (i.e., filtration of the information). Lastly, when time pressure is extreme, people may change strategies. Furthermore, two differences are worth highlighting to consider in our approach. First, the research of Payne et al. (1988) focused on preferences (e.g., between gambles) rather than on cue-based inferences. Second, they measured performance by a correlation of choices with a WADD (the probable payoff) rather than with an external criterion, because there is none for subjective choice. As Czerlinski et al. (1999) explain "only with an external standard for the number of correct inferences is it possible to show that simple heuristics can be more accurate than more complex strategies" (p. 108).

1.2.2. Tasks to Study Decision-making

The general (not exhaustive) classification that Yu (2015) provides helps us to understand the main types of tasks in decision-making. According to the formal, mathematically quantifiable characteristics of the tasks and the potential cognitive processes they may involve, the main types of decision-making tasks can be divided into the following (Yu, 2015): (1) decision-making under uncertainty, (2) multidimensional decision-making and, (3) preference-based decision-making. Our focus will be in the first group but before we provide a general description of the other two.

Within the third group, the research is dedicated to studying the decision-making process of humans and how they choose based on their preferences. Within the second group, Yu distinguishes two main types: (a) target-distractor differentiation, and (b) multisensory integration. In the foremost, subjects are expected to ignore the distracting effects of a distractor stimulus or attribute, to concentrate on the target stimulus or attribute. In type (b) individuals must integrate multiple stimuli of different sensory

modalities to arrive at a combined choice response. The first group encompasses tasks in which individuals have to make choices among options under conditions of uncertainty. The difficulty level of the tasks can be manipulated via the level of uncertainty induced experimentally, which ultimately allows for studying human and animal decision-making cognition (Yu, 2015).

1.2.2.1. Probabilistic Inference Task

Following the view of Gigerenzer et al. (1999), we know people specifically deal with uncertain scenarios of the world using fast and frugal heuristics taken from an adaptive toolbox. In a probabilistic inference task (PIT), part of the decision-making under uncertainty tasks (Shachter & Peot, 1992), people must use different elements of given knowledge to infer the correct state of the world (Rieskamp, 2006; Rieskamp & Hoffrage, 1999, 2008; Wichary et al., 2016). Thus, PITs help us to simulate similar characteristics of people's world, to study what strategies of their toolbox they use under certain conditions (e.g., limited or abundant information, time, environment constraints, etc.); that is, we assume that individuals adaptively choose strategies from a collection to resolve the inference problems of their environment (see Gigerenzer et al., 1999; Payne et al., 1988; Rieskamp & Otto, 2006; Rieskamp & Hoffrage, 2008). Although our aim is not to compare the different approaches to study inferences, we recognize some of the alternatives, such as the connectionist approach (see Gluck & Bower, 1988; Sieck & Yates, 2001), the exemplar-based approach (Juslin et al., 2003; Juslin & Persson, 2002), and the sequential sampling approach (Busemeyer & Townsend, 1993; Wallsten & Barton, 1982).

2. Chapter 2: The Neural Substrate

2.1. The Neural Substrate of Decision-making

The decision-making process is known to be linked to the prefrontal cortex (Carlén, 2017). For over 70 years, this brain region has been defined and characterized as the part of the cerebral cortex that receives projections from the mediodorsal nucleus of the thalamus (MD; Carlén, 2017; Roose & Woosley, 1948). This view has some limitations, and the prefrontal cortex also includes tissue that has projections from the amygdala and to the basal ganglia (BG) and the rest of the cerebral cortex (see also Carlén, 2017, and Kolb, 2015, for a review). Although the subdivisions and their reach vary according to the literature, the common functional divisions (Kolb, 2015) are the dorsolateral (DLPFC), the ventromedial (VMPFC), and the orbital prefrontal cortex (OFC). In addition, some authors consider the anterior cingulate cortex (ACC) to be part of the prefrontal cortex because it receives projections from the MD (Preuss, 1995).

Neuroimaging studies (Farrar et al., 2018; Kringelbach & Rolls, 2004; Krug et al., 2014) and focal studies (Clark & Manes, 2004; Floden et al., 2008) on decision-making have underpinned three major regions of the cerebral cortex to influence this process: the orbitofrontal cortex (OFC), the anterior cingulate cortex (ACC), and the dorsolateral prefrontal cortex (DLPFC). Additionally, subcortical structures such as the BG (caudate nucleus, putamen, globus pallidus, subthalamic nucleus, substantia nigra, and nucleus accumbens), thalamus and cerebellum are interconnected between them and with the cortical regions involved in decision-making (Krawczyk, 2002; Rosenbloom et al., 2012). Further, fMRI studies have also found the OFC, ACC, and DLPFC to play a critical role in decision-making under uncertain conditions (Demanuele et al., 2015; White et al., 2014).

In broad terms, the OFC is connected with the limbic system and it is crucial for

decisions based on the prospect of rewards (reward-based) as well as the emotional experience (affective-based; Krawczyk, 2002). The OFC is characterized by its substantial bidirectional connections with the insular, anterior cingulate, and medial temporal cortices, as well as the amygdala and hippocampus (Barbas, 2007). These networks together with the connections between the OFC, the DLPFC, and the ventrolateral prefrontal cortex (VLPFC), make them responsible for emotional processing (Krawczyk, 2002; Barbas, 2007). The DLPFC is the hub for integrating multiple streams of information (Krawczyk, 2002) and it also has limbic connections and cortico-cortical connections through the temporal, parietal, and occipital cortex (Miller & Cummings, 2007; Pandya & Yeterian, 1996). Injuries to the DLPFC often result in a frontal dysexecutive syndrome; patients have problems with working memory, planning, inhibitory control, strategy development, and cognitive flexibility (Clark & Manes, 2004). The ACC is recruited for extremely ambiguous choices, for example in circumstances where there are conflicting options and a high probability of error, and participates in performance optimization and assessment using previous reward information to guide decisions (Rosenbloom et al., 2012). In other words, the ACC participates in performance optimization and evaluation by using prior reward experiences to guide choices. Further, the ACC is specialized in selecting from competing options, along with outcome processing (Krawczyk, 2002), and presents cortico-cortical connections to the OFC and DLPFC, and subcortical projections to the nucleus accumbens (NA; Rosenbloom et al., 2012).

2.2. The Neural Substrate of Decision Strategy Selection

Several studies on multiattribute choice and its neural correlates have been reviewed by Busemeyer et al. (2019), Venkatraman & Huettel (2012), and Volz & Gigerenzer (2012), while others have also included strategy use (Venkatraman & Beard,

2020; Venkatraman et al. 2009a, Venkatraman et al. 2009b; Wichary & Smolen, 2016; Wichary et al., 2017). Venkatraman et al. (2009a) examined the choices made when making risky decisions using fMRI and found that the activation of the dorsomedial prefrontal cortex (DMPFC) predicts and shapes behavior toward or against individual strategic preferences. In particular, the DMPFC was shown to serve as a functional connectivity center whose role varied according to the strategy used: there was increased connectivity with DLPFC and posterior parietal cortex (PPC) for simplifying strategies (i.e., maximizing the chance of winning) and increased connectivity with the anterior insular cortex (AINS) and amygdala for compensatory strategies. Compensatory strategies aimed to maximize the gains were associated with an increase in activation of the ventromedial prefrontal cortex (VMPFC), while compensatory strategies aimed to minimize the losses were associated with greater activation in AINS. Although the DMPFC alone did not predict which strategy the participants preferred, they did find that the activation of the ventral striatum predicted the individual variability in strategy use. The increased activation of the DLPFC is consistent with the brain regions often linked with executive function and making choices in risk and uncertainty conditions (Bunge et al., 2002b; Huettel et al., 2005, 2006; Levi, 2017; Obeso et al., 2017; Pandi et al., 2022; Paulus et al., 2001; Ye et al., 2015). Furthermore, evidence suggests that the DMPFC presents an anterior-to-posterior functional topography: the anterior part predicts strategic control of decisions, the middle area predicts decision-related control and the posterior part predicts response control of decisions (Venkatraman et al. 2009b; Venkatraman & Huettel, 2012).

Another important brain area of decision strategy selection is the VMPFC. Numerous studies have shown its involvement in the computation of expected rewards driving action selection and predicting action outcomes (Boorman et al., 2009; Boorman

et al., 2011; Clithero & Rangel, 2014; Gläscher et al., 2012; Hampton et al., 2006; Liu et al., 2011; Levy & Glimcher, 2012; Lopez-Persem et al., 2016; Noonan et al., 2010). In terms of network perspective, the VMPFC's reward-processing and decision-making functions are suggested to rely, at least in part, on its interactions with the ventral striatum and amygdala (Hiser & Koenigs, 2018). Human functional imaging studies revealed that the VMPFC and ventral striatum show robust functional connectivity at rest (Cauda et al., 2011; Choi et al., 2012; Di Martino et al., 2008) and are frequently coactivated during tasks involving reward processing (Cauda et al., 2011). Similarly, another fMRI study investigating inference-based multiattribute choice demonstrated an association between strategy selection and the activity of the ventral striatum, the VMPFC, and the ACC (Gluth et al., 2014).

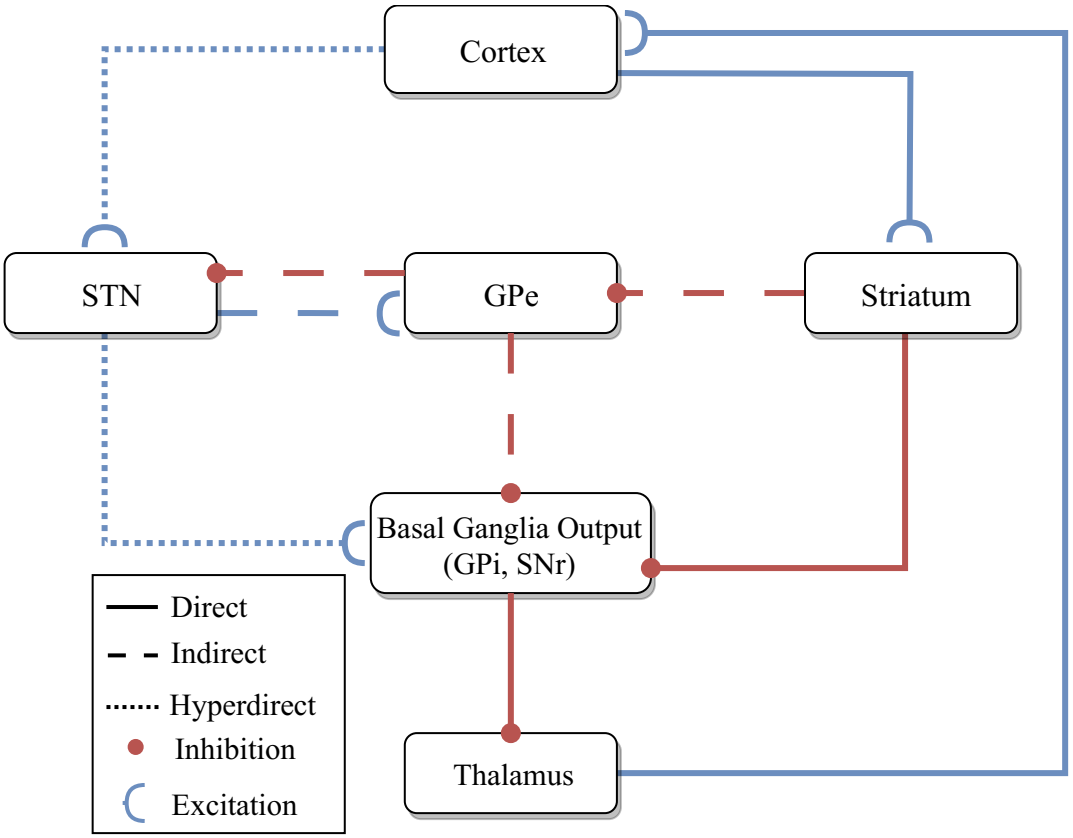
2.3. The Neural Substrate of Inhibition

Multiple lines of evidence support that voluntary action and voluntary inhibition rely on a network of cortical and subcortical structures. Yet, some of the structures involved in the different pathways between the cortical and subcortical areas involved in this process are still debated (Zandbelt et al. 2013; Hannah & Aron, 2021). These three main cortico-subcortical connectivity pathways are (1) the "direct" pathway, (2) the "hyperdirect" fronto-subthalamic-pallidal pathway, and (3) the "indirect" fronto-striatal-pallidal-subthalamic pathway (Alexander et al., 1990; Aron & Poldrack, 2006; Baladron et al., 2019; Mink, 1996; Nambu et al., 2002). The direct pathway (solid lines in Figure 1) describes the route through which voluntary action is initiated, specifically, the 'go' process that activates the premotor cortex going downstream to the striatum (caudate nucleus and putamen) with excitatory neurons. The neurons from the striatum which are inhibitory send their axons to the basal ganglia output (Globus pallidus interna [GPi] and substantia nigra pars reticulata [SNr]) and it communicates via the inhibitory axons with

the thalamus. That is, the GPi/SNr removes their tonic inhibition from the thalamus, also known as disinhibition of the thalamus (removal of inhibition by inhibition). Finally, the thalamus sends its excitatory pathways to M1 to initiate the action (Aron & Poldrack, 2006; Schmidt et al., 2013). The remaining two pathways describe the possible routes on how inhibition of the cortex is reached (Figure 1).

Figure 1

Cortico–Basal Ganglia–Thalamocortical Networks for Action Control



Note. Adapted from Hannah, R., & Aron, A. R. (2021). Towards real-world generalizability of a circuit for action-stopping. *Nature Reviews Neuroscience*, *22*(9), 538-552. Springer Nature. https://doi.org/10.1038/s41583-021-00485-1. *Reproduced with permission from Springer Nature* (License number: 5616380559262)

The hyperdirect pathway has been pushed forward as the prominent action-stopping network part of the action-stopping model (Hannah & Aron, 2021). At a cortical level, it is composed of the right inferior frontal gyrus (rIFG; also referred to as right inferior frontal cortex [rIFC]), and the pre-supplementary area (pre-SMA). According to

Aron et al. (2003, 2004, 2014), the rIFG, within the ventrolateral prefrontal cortex (VLPFC), plays a crucial role in inhibitory control. The activity of the VLPFC has been linked to self-control under diverse categories of task conditions, such as response inhibition, thought suppression, and delay gratification (Cohen & Lieberman, 2010). Pre-SMA, located in the DMPFC (Aron et al., 2007a; Aron et al., 2007b; Floden & Stuss, 2006; Nachev et al., 2007), is functionally and structurally connected with the rIFG (Aron et al., 2014). The subcortical structures comprise the GPi and substantia nigra pars reticulata (SNr) communicated via projection from the subthalamic nucleus (STN), which is directly connected to the rIFG via a white matter tract (Aron et al., 2007b). These cortical and subcortical regions appear to cooperate to send a stop command and suppress the output of the BG, exciting the thalamus and resulting in an inhibitory effect on M1 (Stinear et al., 2009; Aron, 2011). Other studies also suggest the involvement of the ACC (e.g., Forstmann et al., 2012). Moreover, the research of Aron & Poldrack (2006) found that there was a significant activation of ipsilateral structures in the response inhibition process, namely right STN, rIFG, right pre-SMA, right GP, right parietal cortex, and right insula. Their results are in line with earlier neuroimaging studies that revealed that this action-stopping network was right-lateralized and comprised of the IFC, pre-SMA, right parietal cortex, and occasionally thalamic regions (Bellgrove et al., 2004; Garavan et al., 1999, 2002; Liddle et al., 2001; Menon et al., 2001; Mostofsky et al., 2003; Rubia et al., 2003; Simmonds et al., 2008; Swick et al., 2011). In contrast, the hypothesis of Hampshire and colleagues support the idea that the rIFG is not only specialized in inhibitory control and does not play a unique function in inhibition alone but there is a more complex network involved in this process. This network at the cortical level includes the rIFG, the left IFG, the PPC, and the pre-SMA (Hampshire et al., 2010). They hold that at an executive level, tasks that involve stop-go responses such as the stop-signal task (SST)

are represented as two competing and alternate behaviors; concentrating attention on one of the two will lead to inhibit the other (Hampshire et al., 2010). Specifically, evidence suggests that the rIFG plays a role in attentional switching (Cools et al., 2002; Dove et al., 2000; Hampshire & Owen, 2006; Hampshire et al., 2010), that is the cognitive ability to change our attentional focus from one task to another (Monsell, 2003). Similarly, other authors argue that the PFC indirectly executes inhibitory control by monitoring the relevant task and activating goal-relevant processing areas whenever the predominant task schema conflicts with the superordinate behavioral goal (Cieslik et al., 2015).

Studies on the role of the STN (part of the hyperdirect pathway) have proposed that it plays a slightly different role in decision-making. Particularly, the STN executes a "hold your horses" pause (Frank, 2006) when conflict is identified, raising the decision threshold by suppressing basal ganglia output (Bogacz & Gurney, 2007; Wiecki & Frank, 2013; Zavala et al., 2015). One of the hypotheses is that this pause function is executed by different and discernible cortico-STN pathways for dissimilar behavioral contexts (Aron et al., 2016). When action is triggered via the direct pathway, it requires removing GPi's inhibition of the thalamus. However, if a decision under conflicting situations is detected, two or more premotor responses are triggered at the same time. This conflict is detected by the pre-SMA (Taylor et al., 2007; Wiecki & Frank, 2013), which subsequently uses the hyperdirect pathway to recruit the STN (Aron et al., 2016; Hannah & Aron, 2021). The STN, in turn, increases GPi's inhibition of the thalamus (the "pause"). To resolve this pause situation, the corticostriatal input (direct pathway) needs to overpower GPi's inhibition to silence it. In the end, a higher "threshold" of cortical information (evidence) is required to ignite a response. As time passes, the pre-motor representation linked with the correct choice will gain more value until it is selected. This correct response will be associated with longer reaction times compared to low-conflict

trials. However, the extent to which response conflict resolution and stopping depends on shared mechanisms of inhibition (Daniel et al., 2022) is not yet fully understood. Although the results of some studies using Stroop, Eriksen Flanker, and decision tasks (Brittain et al., 2012; Cavanagh et al., 2011; Fumagalli et al., 2011; Zavala et al., 2013, 2014) are consistent with the conflict resolution role of the STN, other studies challenge this hypothesis. For example, a 7T fMRI study revealed that participants displaying high performance in motor response inhibition (short response times in a stop-signal task) show stronger structural connections between the ACC and the right STN, whereas this association did not extend to other connections studied such as the connections from the rIFC to either the left or right STN (Forstmann et al., 2012). In contrast, in a study by Aron et al. (2007a) using diffusion-weighted magnetic resonance imaging (DWI), they found that individuals who inhibit more quickly significantly activate the rIFC and the STN more compared to pre-SMA, which did not show a significant activation.

The indirect pathway has been differentiated into two: the short indirect pathway (striatum, GPe, GPi/SNr) and the long indirect pathway (striatum, GPe, STN, GPi/SNr). The latter recruits also the STN as the hyperdirect pathways do. The key difference in the role of the striatum, specifically the dorsal part, between the direct pathway and the indirect pathways is that it contains mainly two groups of neurons. On one hand, it sends striatal spiny projections neurons (SPNs) that innervate the basal ganglia output nuclei (direct pathway), whereas the other group of SPNs reaches the basal ganglia outputs indirectly via the indirect pathways as described. Although this is beyond the scope of our research, different models explain how and where (i.e., in which group of neurons) the direct and indirect pathways work to exert their functions (see Klaus et al., 2019 for a review). Among these frameworks, the neurocomputational striatal model serves us in our context of decision-making (see Bogacz et al., 2010a for a review). It postulates that

the excitability of the striatum via cortical inputs through pre-SMA gives as a result a change in decision boundaries by modulating the inhibitory effect of BG on efferent neurons (Forstmann et al., 2008, 2010; Tosun et al., 2017). Therefore, when pre-SMA sends excitatory signals to the striatum, this reduces the inhibitory effect of the BG. The BG in turn permits the execution of faster but often premature responses (Bogacz et al., 2010b; Forstmann et al., 2008).

To continue with the implication of the functional role of pre-SMA, it has been shown to have at least a double role: it is a key node of the inhibitory network (Chen et al., 2009; Floden & Stuss, 2006; Picton et al., 2007), and it is important for the preparatory selection and modulation of decision thresholds (Berkay et al., 2018; Georgiev et al., 2016; Ikeda et al., 1999; Nachev et al., 2007; Shima et al., 1996; Tosun et al., 2017). Data from neuroimaging studies, clinical work, and transcranial magnetic stimulation (TMS) shows that the selection of response and inhibition recruit similar brain areas, including the DLPFC, IFG, ACC, and dorsal pre-SMA (Bunge et al., 2002a; Hazeltine et al., 2000; Hazeltine et al., 2003; Koski et al., 2005; Praamstra et al., 1999; Rubia et al., 2001; Rushworth et al., 2002; Schumacher et al., 2003; Schluter et al., 1998; Wager et al., 2005). In theory, the pre-SMA might coordinate both the selection and inhibition of behavior by leveraging the same looped connections with the BG (Chambers et al., 2009). In contrast, TMS (Chambers et al., 2007) and pharmacological studies in clinical populations (Scheres et al., 2003) have shown that these two processes do not fully share the same brain network, leading us to have evidence for both types of theories; either response inhibition and response selection are managed by neural connections that are somewhat different (Chambers et al., 2009), or they share similar neural connections. Thus, further studies are needed to clarify the relative contribution of the pre-SMA and the rIFG in both cortico-basal pathways (Zandbelt et al., 2013; Hannah & Aron, 2021).

3. Chapter 3: Transcranial Magnetic Stimulation

3.1. Functioning and Types of Transcranial Magnetic Stimulation

The first introduction of transcranial magnetic stimulation (TMS) as a non-invasive brain and nerve stimulation technique was made by Barker and colleagues in 1985. TMS is a noninvasive technique, based on Faraday's law of induction, that can induce neural activity in the human brain (Hallet, 2007; Siebner et al. 2022). A short, rapidly changing, high-intensity electrical current circulates through conducting wire inside a protective case (coil), generating a magnetic field. When the coil is placed in any part of the scalp the magnetic field crosses the cranium, inducing an electric current in the underlying cortical brain tissue. The induced current depolarizes nearby neurons located beneath the coil, leading to neuropsychological and/or behavioral effects on an individual depending on the area stimulated, and the parameters and characteristics of the magnetic stimulator (Klomjai et al., 2015). The latter refers to the coil shape (Deng et al., 2014; Thielscher & Kammer, 2004; see Figure 2 for an illustrative example), coil dimension (Deng et al., 2014), coil orientation (Janssen et al., 2015; Mills et al., 1992), coil direction (Niehaus et al., 2000), coil position (Casula et al., 2022; Kozel et al., 2000; Reijonen et al., 2020) and type of stimulator (Thielscher & Kammer, 2004; See Figure 2 for an illustrative example). Additionally, the effects also depend on the magnetic pulse waveform (monophasic or biphasic; Corthout et al., 2001; Sommer et al., 2006), intensity (Rothwell, 2010), frequency (Chen et al., 1997) and interstimulus interval (Kujirai et al., 1993). As a result, TMS can sometimes facilitate or inhibit neuropsychological and/or behavioral responses (Tergau et al., 1997; Watkins & Devlin, 2008).

TMS can be delivered in different forms. When applied as one magnetic pulse at a time it is known as single-pulse TMS, which is commonly used to explore brain functioning (Klomjai et al., 2015). A special case, repetitive TMS (rTMS), consists of

the application of trains of magnetic pulses delivered at a fixed frequency (usually between 1-20 Hz). In rTMS, when the magnetic pulse frequency is lower than 1 Hz (low-frequency) it decreases cortical excitability and reduces motor evoked potential (MEP) amplitude (if applied to the primary motor cortex, M1), leading to inhibitory effects. This effect has been measured to last for at least 60 min (Lyer et al., 2003.) In contrast, when the pulse frequency is between 5-25 Hz (high-frequency) it increases cortical excitability

Figure 2

Illustration of a Type of Transcranial Magnetic Stimulator and Coil

Note. Magstim Rapid 2 Transcranial Magnetic Stimulation (TMS) machine connected with a Standard Coil, made by Magstim Ltd c.2006. Retrieved from Science Museum Group. (2023). Transcranial Magnetic Stimulation Machine [2011-10/1]. Science Museum Group Collection Online. https://collection.sciencemuseumgroup.org.uk/objects/co8081243/transcranial-magnetic-stimulation-machine-cranial-stimulation-device. *Reproduced under Attribution-NonCommercial-ShareAlike 4.0 International (CC BY-NC-SA 4.0).*

and increases MEP amplitude (if applied to M1), leading to excitatory effects (Chen & Seitz, 2001). However, the duration of the after-effects caused by high-frequency rTMS depends on the intensity of stimulation, number of pulses, and frequency of stimulation. In some cases, the effects of high-frequency rTMS can last up to 90 minutes after stimulation (Klomjai et al., 2015). In broad terms, both types of rTMS are used to induce changes in brain activity that can outlast the stimulation period.

Another form to deliver TMS is a relatively new rTMS protocol introduced by Huang et al., (2005), known as theta-burst stimulation (TBS), which consists of many bursts of magnetic pulses at a given frequency (i.e., rTMS), repeated at specific intervals. TBS protocols are characterized by delivering less stimulation in time and lower intensity than other rTMS protocols. Depending on how the stimulation is administered we can differentiate between continuous TBS (cTBS) and intermittent TBS (iTBS). During cTBS there is no inter-stimulus interval (ISI) between the trains of magnetic pulses (i.e., continuous train of TBS bursts), whereas during iTBS, there is a predefined ISI. Additionally, cTBS has been shown to produce cortical inhibitory effects (predominately more than the initial facilitatory effects), while iTBS favors a rapid increase of facilitation (i.e., increase motor cortical excitability; Huang et al., 2005; Huang et al., 2011; Wischnewski & Schutter, 2015).

TBS has the advantage over rTMS in that a stimulation delivered in a period between 20 and 190 seconds (brief period) causes changes in cortical excitability that outlast the time of stimulation for at least 20-30 min (Cárdenas-Morales et al., 2009). In a review article of sixty-four TBS studies, Wischnewski & Schutter (2015) found that iTBS applied for 190 s significantly increases cortical excitability up to 60 min. In contrast, cTBS applied for 20 s depresses the cortex for up to 20 min, while if applied for 40 s the decrease of cortical excitability can reach up to 50 min. TBS appears to be a

useful technique to modulate motor cortex physiology and behavior in healthy individuals (Huang et al. 2007; Talelli et al. 2007a; Teo et al. 2007). It may also be useful as a therapeutic tool in some neurological and psychiatric disorders (Di Lazzaro et al. 2006; Talelli et al. 2007b). However, the disadvantages are similar to those observed in other rTMS protocols. For example, it is unclear if continuous TBS (cTBS) and intermittent TBS (iTBS) over non-motor areas produce the same modulatory effects (Cárdenas-Morales et al., 2009).

Three basic groups can be used to classify study designs that use TMS (Valero-Cabré et al., 2017): (a) online, (b) offline, and (c) chronometric studies. The design of online TMS protocols consists of administering single pulses or short stimulation bursts at high frequencies to intervene in the contribution of a targeted region while engaging in a particular behavior (e.g., a task). In particular, TMS induces depolarization in a considerable amount of neurons, which causes them to enter a refractory state and temporarily halt their processing capabilities. Online TMS is also thought to have the effect of incorporating disruptive electrical signals that resemble "noise" distorting neuron interactions (Valero-Cabré et al., 2017). Further, changes in performance are evaluated by having individuals undergo a task while receiving the transcranial magnetic pulses and contrasting the effects of active TMS to sham TMS (or active stimulation in a control site) trial-by-trial. In offline TMS designs, the changes in performance are measured after the repetitive magnetic pulses have been delivered. This is due to evidence suggesting that following TMS administration in long patterns of single pulses at a given frequency (at least 1 Hz), cortical activity remains altered (Allen et al., 2007; Aydin-Abidin et al., 2006; Romero et al., 2002; Valero-Cabré et al., 2006) for an average period of 30 minutes after the stimulation (Huber et al., 2007; Thut & Pascual-Leone, 2010; Van Der Werf & Paus, 2006), and in some cases up to 60 minutes (Schindler et al., 2008).

Lastly, chronometric studies fall under the category of online designs. In this research, one hypothesizes how the stimulated area may contribute to a behavioral response by applying TMS in single pulses or brief bursts within a particular time frame. The frequency of these pulses typically ranges from 10 to 50 Hz, with up to 3-4 pulses, depending on the necessary temporal resolution. Researchers can evaluate and comprehend the causal relationship and temporal dynamics of these brain contributions to behavior by viewing and comparing the outcomes of administering these pulses at various temporal intervals (Valero-Cabré et al., 2017).

3.2. Repetitive Transcranial Magnetic Stimulation in the Inhibitory Network

Most of the literature on the inhibitory network using TMS was conducted using the stop-signal paradigm or its variants. For example, in a TMS study, three conditions of TBS (continuous, intermittent, and sham) were applied over the rIFG of participants before they underwent a stop-change task to study the effects on processing strategies (Dippel & Beste, 2015). Results show that iTBS of the rIFG induced an enhancement in strategy selection during the task, while cTBS of the rIFG led to a less efficient strategy selection compared with sham cTBS control condition. This suggests that the neural dynamics of the rIFG determine the strategy used during some forms of behaviors that require complex motor plans in situations that demand a composition of different actions to achieve a goal (Dippel & Beste, 2015). Another study showed that after applying offline 1-Hz rTMS targeting the rIFG, it slowed stop signal reaction time (SSRT; Sundby et al., 2021), which could causally indicate the inhibitory role of the rIFG. Moreover, an offline rTMS protocol was used to alter the neural activity in the rIFC and SMA followed by fMRI scans and a modified stop-signal task to analyze the effects on activation in the networks involved in inhibitory control (Zandbelt et al., 2013). rTMS was shown to have effects only in reactive inhibition (outright stopping in response to a stop signal). The

authors found that after stimulating rIFC and SMA the stop signal response time (SSRT) was shortened and it was linked with increased M1 deactivation. Additionally, this protocol increased right striatal activation after rIFC and SMA stimulation, which involved frontostriatal pathways in reactive inhibition. Lastly, rIFC stimulation modified SMA activation, but SMA stimulation did not change rIFC activity, suggesting that rIFC is located upstream of SMA. In a different study, rTMS was used to study the functions of the superior parietal lobe (SPL) and IFC in both hemispheres in a deductive reasoning task which included congruent, incongruent, and abstract trials (Tsujii et al., 2011). The results were also examined to what extent supported the dual-process theory of reasoning, which suggests that there are two diverse human reasoning systems: a belief-based heuristic system; and a logic-based analytic system. Stimulation of bilateral SPL interfered with the performance of abstract and incongruent reasoning. Incongruent reasoning was paradoxically facilitated while congruent reasoning was impaired by left IFG stimulation. In contrast, incongruent reasoning performance was only impaired after rIFG stimulation. These results are in line with the dual-process theory of reasoning: while the analytical system may be supported by bilateral SPL, the heuristic system may be associated with the left language-related IFG. Additionally, the impairment of the inhibitory function of the rIFG caused participants to not respond correctly for incongruent trials, suggesting that this area may have a blocking function in the belief-based heuristic system for this type of reasoning. Lastly, Obeso et al. (2017) studied the causal contribution of pre-SMA and rIFG in response inhibition by using cTBS before participants completed a conditional stop-signal task. They found that after applying cTBS over pre-SMA, it improved the motor response (faster the participants inhibited) compared to sham cTBS and the rIFG cTBS. Surprisingly, stimulation over rIFG did not induce any significant change in the inhibitory response compared to sham cTBS.

Another acumen of research on the causal role of pre-SMA using TMS is in perceptual decision-making studies investigating the tradeoff between speed and accuracy of choices (SAT). Tosun et al. (2017) used offline cTBS on right pre-SMA and sham over vertex (control) before participants underwent a two-alternative forced-choice decision task. They found that after inhibiting pre-SMA, participants showed a more cautious behavior by setting higher decision thresholds compared to the control site. In a follow-up study by Berkay et al. (2018), offline cTBS and iTBS were administered over right pre-SMA before participants completed a moving dot task. The results of this study build up on the previous ones by providing causal evidence that inhibition of pre-SMA (cTBS) leads to an increase in the decision threshold, whereas excitation of pre-SMA (iTBS) leads to a decrease in the decision threshold. Further, a single-case study of a patient with a focal lesion in pre-SMA, age-matched against 52 controls performing computational modeling of a stop/no-go task revealed that the patient had an increased response time to stop action as a result of an uncommon low response threshold (Wolpe et al., 2022). This suggests that pre-SMA may exert a dynamic threshold modulation to regulate and control actions. However, another TMS study showed that cTBS over pre-SMA led to a decrease in the decision thresholds but only in the trials where the instruction was to be accurate, failing to modulate it on speed trials (Georgiev et al., 2016). Consequently, rTMS and TBS can be used to disturb and study the inhibitory network as it is possible to establish the causal relationship between the activity of the areas involved in this network and a specific function (Eisenegger, et al., 2008).

4. Chapter 4: The Research

4.1. Background Summary

Individuals have to make decisions on a daily basis to function independently and to successfully adapt to our context. These decisions can range from the simplest ones, such as deciding what to prepare for breakfast to more complex ones like buying a car, building our financial portfolio, or whether to relocate to another country or not. One of the pathways to making a choice is through the use of heuristics, unconscious (and conscious) strategies that allow us to overlook pieces of information to decide faster, to prevent excessive expenditure of cognitive resources, time, money, or even to be more precise instead of employing intricate approaches. Among the theories to study decision-making, there are normative theories which include a vision of unbounded rationality in which individuals and their decision-making strategies have no limits regarding time, knowledge, or computational capacities, and descriptive theories which consider individuals' decision-making as bounded (limited). We follow a descriptive theory proposed by Gigerenzer and colleagues (1999) which considers that people's minds incorporate an "adaptive toolkit" containing several heuristics or shortcuts. These are also viewed as simple rules that allow us to make smart choices in an adaptable manner depending on the various types of environmental structures (Gigerenzer et al., 1999; Rieskamp & Hoffrage, 1999; Todd & Gigerenzer, 2000, 2012).

By virtue of the term "ecological rationality," Gigerenzer and colleagues explain when and how the heuristics from the adaptive toolbox are indeed adapted to the environment in which we operate. A heuristic success is determined by comparing it against an environmental criterion, that is the ecological structure in which it is applied, and secondly, by measuring the fit between the structural qualities of the shortcut and the structure of the environment in which is used (Martignon & Hoffrage, 1999; Hoffrage,

2014). In other words, both the heuristics and the environment have a structure, which can be of two types: noncompensatory or compensatory (Martignon & Hoffrage, 1999, 2002). In noncompensatory environments, the most significant cues hold greater weight and cannot be outweighed by any combination of less significant cues. Conversely, in the latter environment, one or more cues can be offset or balanced out by a combination of less significant cues. Among the strategies from the toolbox TBB and WADD are the two of our relevance, because these are often successful in describing people's inferences (Bröder, 2000, 2003; Rieskamp & Hoffrage, 2008; Wichary et al., 2016). In particular, WADD is the optimal strategy against which to compare heuristics as is both "the traditional gold standard for rational preferences" and inferences (Gigerenzer et al., 1999; Shah & Oppenheimer, 2008). When decision-makers use the compensatory strategy WADD, they consider all of the available alternatives and cues for each alternative to arrive at an added and overall value for an alternative (for the exact procedure see "Decision-making Theories and heuristics taxonomy"). In contrast, when using the noncompensatory-lexicographic heuristic TTB, one chooses an alternative according to the cue with the highest validity (Gigerenzer & Goldstein, 1999). One way to investigate these strategies within the scope of studying decision-making in individuals is the PIT, a decision-making under uncertainty task that allows us to model similar characteristics of our world to study what toolkit strategies people use under specific circumstances.

The decision-making process requires a degree of cognitive control to reason, plan, inhibit, and hold information in our working memory to regulate our thoughts and behaviors in a different direction from those that arise automatically (Kool et al., 2017). Additionally, both inhibitory mechanisms, one centered on withholding motor actions (response inhibition) and the other focused on tolerating the disruption from environmental factors outside the body (attentional inhibition) contribute to the decision-

making process when choosing among potential responses. Particularly, they are necessary to improve our decision-making (Xu et al., 2020) by selecting better behavioral options that are in line with one's goals (Li et al., 2022). In broad terms, while the decision-making process mainly involves the OFC, ACC, DLPFC, the BG, thalamus, and cerebellum (Krawczyk, 2002; Rosenbloom et al., 2012), the neural substrate of strategy selection includes the DMPFC, DLPFC, PPC, VMPFC, AINS, ventral striatum and ACC (Gluth et al., 2014; Cauda et al., 2011; for a review see Venkatraman & Beard, 2020).

Regarding inhibition, the basal ganglia models propose two main pathways through which this function can be exerted to stop and regulate the activity on the direct pathway: the hyperdirect and the indirect pathway (Aron & Poldrack, 2006). In the first one, pre-SMA and rIFG send the stop signal via the STN. The fast route between the STN and the GPi (due to the short-latency, monosynaptic connections) makes this section the hyper-connection between these structures. Consequently, the activation of GPi happens because of the STN output, resulting in the subsequent suppression of thalamic excitatory impulses directed towards M1, ultimately reducing the possibility of movement (Hannah & Aron, 2020). Studies focused on the role of STN in the hyperdirect pathway provided evidence that the STN functions as a “hold your horses” pause center (Frank, 2006), via the previous detection of a conflictive decision by the pre-SMA (Taylor et al., 2007; Wiecki & Frank, 2013). Under this framework, enough threshold of evidence is needed at a cortical level (pre-SMA) to overcome the “pause” that the STN exerts over GPi, which in turn inhibits the thalamus. Once this threshold is reached by an accumulation of evidence, the correct choice is selected via the direct pathway (with no involvement of the rIFG). Therefore, at least two models of the hyperdirect pathway can be distinguished at a cortical level: one that includes the pre-SMA and rIFG, which responds upon a stopping signal, and one that considers only pre-SMA, which activates in conflictive

decisions (both continue to the STN; Aron et al., 2016). Within the hyperdirect pathway but in contrast to the proposition of Aron, Hannah, and colleagues, the line of research of Hampshire and colleagues holds that the role of the rIFG is not primarily of inhibition but it is also involved in other functions such as attentional switching (Cools et al., 2002; Dove et al., 2000; Hampshire & Owen, 2006), making the rIFG a center that hosts subregions of various functional networks (Hampshire, 2015; Hampshire & Sharp, 2015a; Hampshire & Sharp, 2015b). In the indirect pathway, there are also two, but clearer, pathways: the short indirect pathway (striatum, GPe, GPi/SNr) and the long indirect pathway (striatum, GPe, STN, GPi/SNr). The striatal framework proposes that is the pre-SMA which regulates the excitability of the striatum via decision boundaries. When a certain threshold in pre-SMA is crossed (also by accumulation of evidence) it sends excitatory signals to the striatum, which reduces the inhibitory effect of the BG, and these in turn permit the execution of faster but often premature responses (Bogacz et al., 2010b; Forstmann et al., 2008).

The inhibitory networks mentioned have been studied in patients with prefrontal lesions (Aron et al., 2003), using different techniques, some of them already mentioned, namely with fMRI (Garavan et al., 1999; Konishi et al., 1999; Aron & Poldrack, 2006; Aron et al., 2007a), TMS (Chambers et al., 2006; Verbruggen et al., 2010), electrocorticography (Bartoli et al., 2018; Swann et al., 2012), DWI (Aron et al., 2007a; Madsen et al., 2010), and more recent studies combining electroencephalography (EEG), TMS, and electromyography (EMG; Hannah et al., 2020; Jana et al., 2020; Sundby et al., 2021). From these techniques, TMS is a promising method because it allows for establishing a causal relationship between the effects induced in brain areas and sensory-motor processing (Polanía et al., 2018).

4.2. Aims of the Study and Hypotheses

Our study aimed to use a cTBS protocol in healthy participants to test the causality of the brain areas involved in the inhibitory network after undergoing a PIT, focused on decision strategy use. The PIT was modified from its earlier versions to include both compensatory and noncompensatory environments (Mata et al., 2007; Wichary et al., 2016; Wichary et al., 2017). To the best of our knowledge, no literature has been published on the confluences of this method and paradigm to study the inhibitory network. As reviewed, most of the TMS protocols aimed to study the inhibitory network are combined with a stop-signal paradigm. Additionally, not many studies used the same TMS protocol that we employ (inspired by the study of Zandbelt et al., 2013) to study the role of inhibition and its neural substrate in decision-making (e.g., changing strategies). Furthermore, at a neuroscientific level, studying the inhibitory network is fundamental to understanding other cognitive processes as well such as attention, impulse control, and decision-making. This could help to understand how our brain works to regulate and control its activity, and the connectivity and dynamic between brain regions. Moreover, from a clinical perspective, inhibitory dysfunction has been linked to various neurological and psychiatric disorders such as deficit hyperactivity disorder (ADHD), schizophrenia, and substance use disorders. Ultimately, unveiling the precise brain areas and brain connections involved in inhibitory control could help to develop cognitive training programs, pharmacological treatments and identify outcome measures that better predict an inhibitory dysfunction, among others.

We hypothesized the following: (1) Following the adaptive decision-maker hypothesis by Payne et al. (1988), we expect that the number of cues taken, decision time, and the relative strategy preference that individuals choose will be consistent with the environment structure. Therefore, we expect that people who take a higher number of

cues and have longer response times will have a relative strategy preference for WADD over TTB in the compensatory environment (and the opposite too); (2) In line with Aron and colleagues' line of research and the hyperdirect pathway that includes pre-SMA and rIFG, cTBS stimulation over rIFG will result in a significant decrease in the number of cues taken and decision time, as well as a significant increase in the relative strategy preference for TTB over WADD compared to-sham stimulation. We expect to see this effect be moderated by the environment structure; (3) In adherence to the subthalamic theory and the hyperdirect pathway that includes only pre-SMA (Aron et al., 2016), cTBS stimulation over pre-SMA will lead to a significant decrease in the number of cues taken and decision time, as well as a significant increase in the relative strategy preference for TTB over WADD when compared to sham stimulation. We expect to see this effect to be moderated by the environment structure.

4.3. Method

4.3.1. Participants

A total of eighteen subjects participated in the study, all right-handed, ranging in age from 20 to 35 years (M = 24.94, SD = 4.33) of both sexes (61% female). They were recruited from a database part of a joint project of several universities which included the Jagiellonian University (JU) and other research institutes under the European Cooperation in Science and Technology (COST) action. Before starting with the study each participant read a leaflet containing information on the experiment (Appendix A), signed an informed consent form (Appendix B), consented to processing their data (Appendix C), and filled in a questionnaire on health and safety aspects related to TMS (Appendix D). One participant dropped the study after the first session as he reported dizziness, fatigue, and feeling anxious after receiving a part of the TMS stimulation. The final sample comprised a total of 17 participants (11 females), with a mean age of M = 25.12 (SD = 4.40), ranging

from 20 to 35 years. The sample size of this study represents 36% of the intended total (50 participants). All participants received a remuneration based on an hourly rate of PLN 50/hour with the possibility of receiving an additional bonus of up to PLN 50 based on the results obtained. The study was approved by the Ethics Committee of the Institute of Psychology, Jagiellonian University. The safety measures taken before and during the TMS sessions were per the latest guidelines for TMS research (Rossi et al., 2021).

The exclusion criteria were: age under 18 or over 35; pregnancy (or suspicion thereof); have or have had a serious head injury, brain damage, or surgery; have an active implant, such as a pacemaker, insulin pump, or neurostimulator; have or have had epilepsy, convulsions, or seizures; have or have had large metallic parts or ferromagnetic parts in their head (except for orthodontic brackets); suffer from a neurological or psychiatric illness (including severe headaches); have suffered from fainting.

4.3.2. Design

All participants underwent three cTBS sessions to implement three stimulation conditions on three different days: rIFG stimulation, pre-SMA stimulation, and sham stimulation to the right superior parietal lobule (i.e., to the vertex; RSP). In each day the participants received one of the three conditions in a randomized order. The minimum time difference between each session was seven days (a total of three sessions, one for each condition). Through a within-subjects design, each participant underwent the PIT in either its compensatory or noncompensatory form (environment structure), which was also randomized at the beginning of each session. Additionally, the structure of the PIT consisted of 36 trials and it was analyzed in blocks of six trials (a total of six blocks).

4.3.2.1. TMS Parameters and Site Localization

The offline cTBS protocol (Zandbelt et al., 2013) consisted of the administration of 200 5-Hz bursts, each containing 3 pulses at a frequency of 50 Hz (total of 600 pulses)

within 40 s, at an intensity of 80% of the individual resting motor threshold (RMT). The same coil was used to deliver the sham condition at 45° in the vertex at 70% of the individual RMT.

The coordinates of the stimulation areas were in the rIFG [56, 16, −4], the pre-SMA [8, 0, 68], and in the rSPL [28, −56, 60] for the sham stimulation using the Montreal Neurological Institute system (MNI; Zandbelt et al., 2013). Sham stimulation over the rSPL was delivered with the coil at 45 degrees with respect to the participant's scalp. The sites of the stimulation were obtained from the translation of the general MNI space to the individual structural MRI images obtained for each participant in a previous MRI study and then projected into coordinates into the skull structure of each participant, according to the guidelines in Brainsight TMS User Manual, v 2.3.

4.3.2.2. EMG Acquisition

The electromyographic signal was recorded with a three-multi-channel electrode grid to estimate the participants' individual RMTs. One electrode of 42x56mm was positioned on the dorsum of the distal phalanx of the index finger, below the level of the nail bed. The same type of electrode was placed distally to the former at the level of the second metacarpophalangeal joint. The last (wet) electrode was positioned at mid-forearm level, between the olecranon and the ulnar styloid.

4.3.2.3. Apparatus and Materials

TBS was delivered using a double 70mm windings coil (D70mm Air Film Coil) using a Magstim Rapid^2 magnetic stimulator (Magstim Company). All stimuli were displayed in the center of a 27"ASUS PA279Q monitor with a 2K resolution (2560x1440), an IPS panel, and a monitor hood to prevent external light sources from interfering with the stimuli presented on the monitor. Behavioral tasks were displayed in the monitor using Python scripts which were run on a computer with Windows 10 Pro,

an Intel Xeon CPU E5-1620 v4 3.60 GHz processor with 16GB of RAM. A neuronavigation system Polaris Vicra Position Sensor model 8700601.001 was used to guide the position of the coil according to the participant's structural MRI image.

For the estimation of the RMT, EMG signals were recorded using two Vermed Lead-Lok R-LLL-510 electrodes with a size of 42x56mm and a wet electrode connected to a Brainsight2™ EMG Isolation Unit and amplifier. All data were collected and stored on an iMac computer running Brainsight® 2 TMS neuronavigation software version 2.3.10 (NeuroConn, Germany), except for the results of the behavioral tasks which were stored in a computer running Windows 10.

4.3.2.3.1. Behavioral Tasks.

Probabilistic Inference Task – Diamond Task (DDT).

The computerized probabilistic inference task (PIT) entailed making decisions about which of two diamonds (A or B) was better to buy according to its characteristics. The qualities of the diamonds were described based on six cues: size, transparency, shape, color, brilliance, and proportions. Numbers 0 and 1 were used to code the cue values, with 0 denoting a low value and 1 denoting a high value. The task had a version representing a compensatory environment structure and another representing a noncompensatory environment structure (Martignon & Hoffrage, 1999). The corresponding cue validities were 0.71, 0.69, 0.67, 0.65, 0.62, 0.60 for the compensatory structure, and 0.93, 0.69, 0.64, 0.62, 0.62, 0.58, for the noncompensatory environment. The cue validities represented the conditional probabilities of selecting the correct option given that the cue differentiated between the

alternatives (Rieskamp & Hoffrage, 1999). A permutation-based computer simulation was used to generate the cue validities and the cue values for each trial in order to produce stimuli sets with both a compensatory and a noncompensatory distribution of cue validities. As a result, both environments were created to maximize the number of items where the choices made between WADD and TTB strategies were different (discriminative items). In consequence, this task allowed us to identify which individual decisions followed the WADD rule and the TTB heuristic. The cue validities were shown in the instructions, together with the information that the presentation of the cues will be displayed sequentially in the descending order of the validities, from the highest cue validity to the lowest. During task performance, participants first saw a fixation point in the center of the screen for 2000 ms, followed by two self-assessment manikins (SAM; Bradley & Lang, 1994), one to evaluate their degree of subjective arousal and the other to evaluate the subjective valence (positive-negative) of their current mood. Participants used the "arrow right" or "arrow left" to rate their answer from a slider on a scale of five SAMs and they confirmed with "arrow down". Afterward, the diamond choice prompt was displayed, followed by arrows prompting the participant to either request a clue or make the choice. They chose by pressing "arrow left" for option A or "arrow right" for option B, while to request the cues they needed to press "arrow down" on the keyboard with their right hand. If the subject

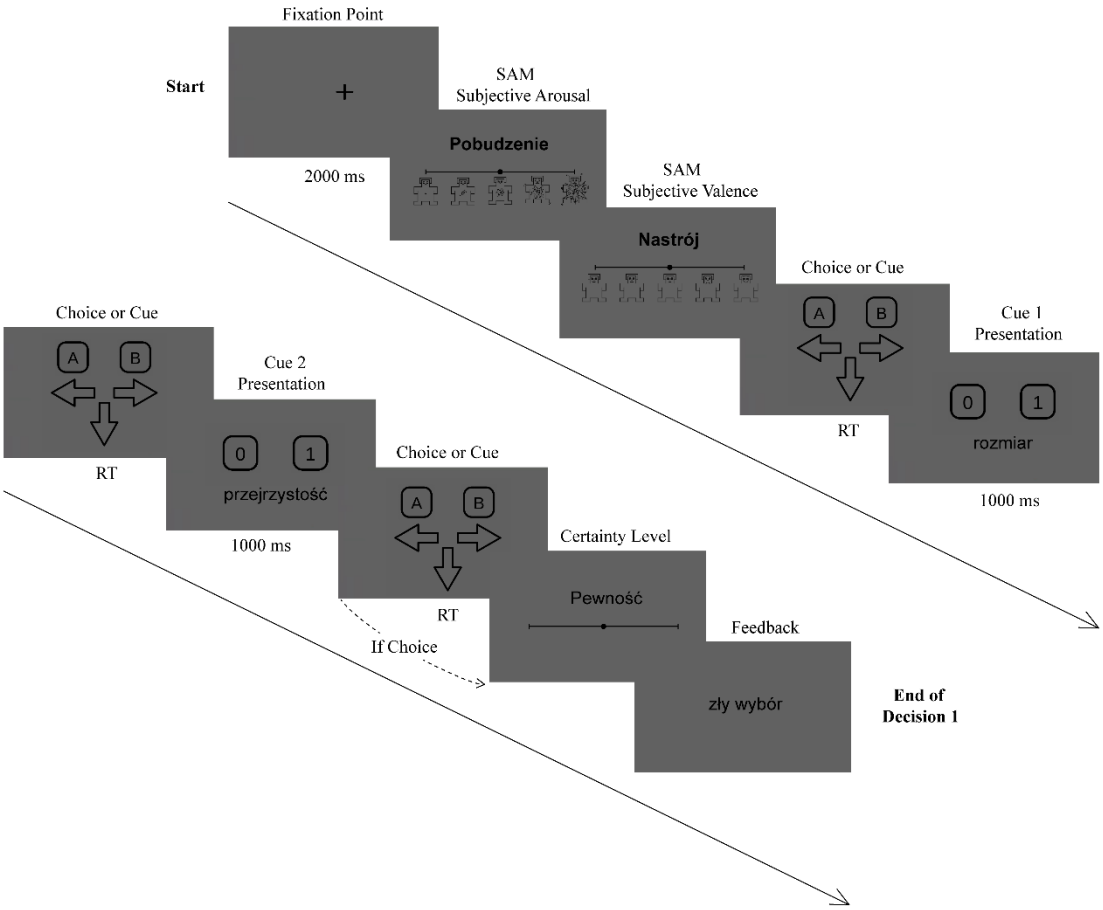
first pressed the “arrow down” button, the cue values for both alternatives appeared on the screen for 1000 ms, followed by the previous choice prompt to either acquire another cue or make the choice. After the participant chose an option, a slider asking how confident they were with their decision was shown. Finally, a feedback message appeared informing the participant whether the choice was correct or incorrect (See Figure 3). The DDT consisted of an instruction phase, a training phase of three decisions, and a test phase of 36 decisions.

Stop Signal Task.

The stop signal task (SST) consisted of a binary-choice response task. It included a primary visual go stimulus consisting of one arrow pointing to the left or right direction which was shown for 100ms on a grey background, approximately 80 cm in front of the participant, at eye level. Participants were instructed to press the left Ctrl key if they saw the left arrow or the right Ctrl key if they saw the right arrow using their index fingers as quickly as possible. The visual stop signal consisted of a red circle that was displayed around the arrow after a stop-signal delay (SSD) of 0.1, 0.15, 0.2, 0.25, 0.3, 0.3, or 0.4 seconds. The stop signal was shown for 1000 ms and the maximum time that the participant had to respond was 1000 ms. Before the presentation of each stimulus, a fixation cross was shown for 800 ms, immediately followed by the presentation of the arrow (i.e., no break time).

Figure 3

Probabilistic Inference Task (PIT) – Diamond Task (DDT)



Note. SAM: self-assessment manikins; RT: reaction time

4.3.2.3.2. Questionnaires.

State-Trait Anxiety Inventory (STAI).

The administered STAI is the Polish adaptation by J. Strelau, T. Tysarczyk, and K. Wrześniewski (Wrześniewski & Sosnowski, 1987; Appendix E) of the original version developed by C.D Spielberger, R.L. Gorsuch, and R.E. Lushene (Spielberger et al., 1970; Speilberger, 1983). This questionnaire is used to assess anxiety levels and has two forms. The first one (STAI X-1) measures state (situational) anxiety, that is, anxiety related to a specific situation or event. The second one (STAI X-2) measures

trait anxiety, which is anxiety that is specific to an individual and not related to a specific situation or event. Each form consists of a total of 20 questions, rated on a 4-point Likert scale, from 1 (almost never) to 4 (almost always). Higher scores indicate higher levels of anxiety.

Barratt Impulsiveness Scale-11 (BIS-11).

The administered BIS-11 is the Polish adaptation (Grzesiak et al., 2008; Appendix F) of the original version (Patton et al., 1995). This scale is a self-report questionnaire with 30 items designed to evaluate three main factors of general impulsivity: attentional, motor, and non-planning impulsiveness. The items are scored through a 4-point Likert scale, from 1 (rarely/never) to 4 (almost always/always). Higher scores indicate a higher level of impulsivity.

Need for Cognitive Closure Scale (NFCC-SF).

The NFCC scale in its short version (Polish adaptation: Bar-Tal & Kossowska, 2010; Kossowska, 2003; Appendix G) was developed from the original version created by Webster & Kruglanski (1994). The need for cognitive closure refers to the need to obtain an answer on a given topic while avoiding confusion and uncertainty and the need to decide as soon as possible (Kruglanski, 1990; DeBacker & Crowson, 2008). This scale is a self-report questionnaire with 15 items rated on a 6-point Likert scale from 1 (completely disagree) to 6 (completely agree). Higher scores are interpreted as a higher need for cognitive closure.

4.3.2.4. Procedure

The study took place at the TMS Laboratory of the Institute of Psychology of Jagiellonian University, located at the Department of Neurology of the University Hospital in Krakow. The sessions were scheduled and performed according to participants' availability with at least one week of difference to reduce the influence of task learning. The entire TMS study lasted about six hours for each of them, with an allotted time of two hours per session. Real stimulation over the rIFG and pre-SMA, as well as sham stimulation, were administered in three separate sessions. The sequence of these sessions was randomized for each participant.

In the first session, participants read a leaflet containing information on the experiment, signed the informed consent, consented to process their data, and completed the TMS health and safety checklist. Next, they filled in the STAI state (X-1) and trait version (X-2), BIS-11, and completed the SST on the computer. Subsequently, EMG signals were recorded from the first dorsal interosseous (FDI) muscle of the right index finger to evaluate the resting motor threshold (RMT). Stimulation was delivered by applying 30% of the maximum stimulation output (MSO) of single-pulse TMS to the left M1. Then, by changing the intensity of stimulation, the location where the suprathreshold TMS induced the maximum spasm was determined in the right FDI index muscle. The lowest intensity resulting in motor-evoked potentials (MEPs) with peak-to-peak amplitude greater than 50 μV was determined in 5 out of 10 consecutive trials. Following RMT determination, participants received the cTBS protocol in the right hemisphere under one of the three conditions (rIFG, pre-SMA, sham to rSPL). Afterward, they completed the two versions of the DDT, implementing the two experimental conditions: compensatory vs. noncompensatory task structure in a counterbalanced order. After they completed the PIT, the participants were asked to complete the STAI X-1 for a second

time and the NFCC-SF. Additionally, the measurement of the EMG signal was ended, and the electrodes were removed. In the second and third sessions, participants were first given the TMS health checklist and only the STAI X-1, and completed the SST. Next, the electrodes for the EMG signal recording were placed, followed by the administration of the TMS protocol in one of the two remaining site locations. Then, they completed the two versions of the DDT and right afterward they filled in the STAI X-1 for a second time within that session. In the last session, we thanked and paid the participants. A schematic representation of the procedure is shown in Figure 4.

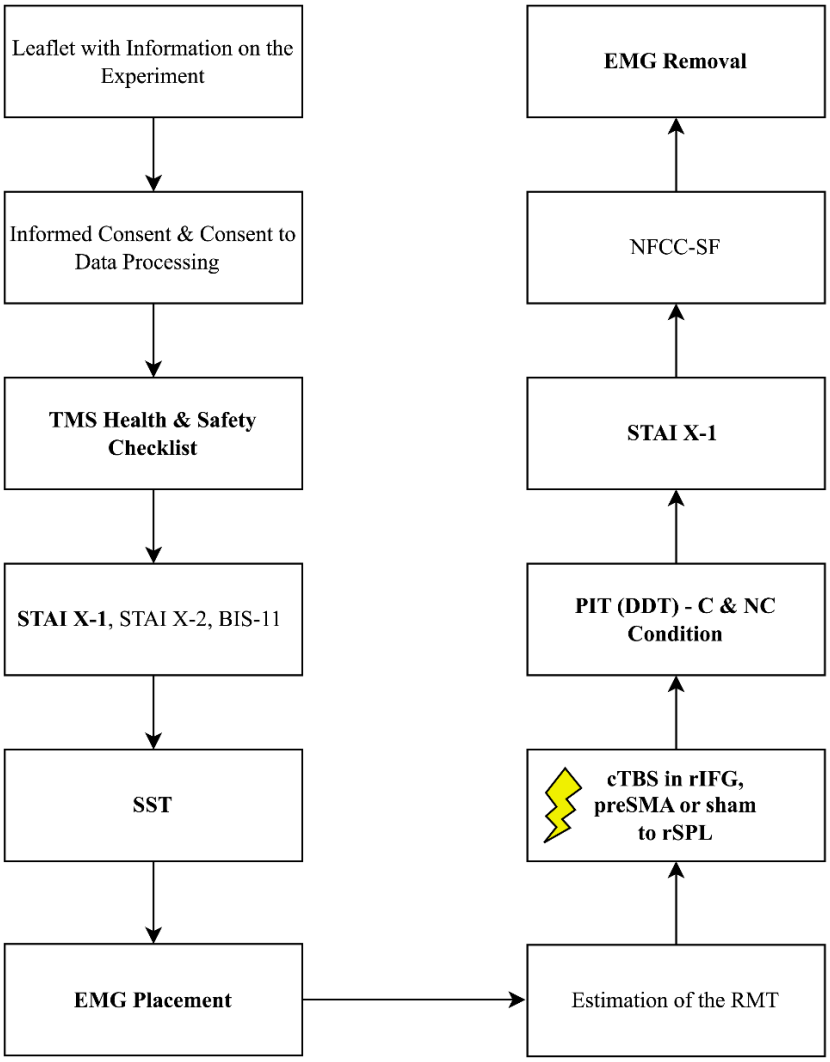
During the whole session, the white lights of the laboratory were turned on. Only when the participant needed to complete the SST and DDT tasks the experimenters moved to a contiguous room. Participants' performance was followed remotely using TeamViewer v15.40.8 (2023). For the TMS protocol, the participants and the experimenters wore earplugs to protect them from the noise of the stimulator. Participants were seated in a comfortable chair at a distance of ca. 70 cm from the screen.

4.3.3. Data Processing

The raw data obtained from the PIT task was preprocessed with a Python script designed for this research to extract the variables of interest. The dependent variables were the number of cues acquired, decision time, and relative strategy preference. The independent variables were the stimulation sites (rIFG, pre-SMA, and sham to rSPL), the environment structure (compensatory and noncompensatory), and blocks of trails. The block of trials was set in groups of six trials each, similar to the approach of Rieskamp & Otto (2006).

Figure 4

Schema of the Procedure for the Sessions



Note. Session 1 is represented in the full schema. Sessions 2 and 3 are represented by bold letters.

4.3.4. Statistical Analysis

Several sets of ANOVAs were performed to investigate the effect of applying cTBS over the rIFG, pre-SMA, and rSPL, the environment structures, and blocks of trails on three dependent variables: number of cues acquired, decision time, and relative strategy preference. Sphericity was met for all ANOVAs except for the interaction effect between environment structure and blocks of trials on the number of cues taken (Mauchly's $W = .02$, $p < .001$) and the blocks of trials on decision time (Mauchly's $W = .11$, $p = .006$). Thus, the degree of freedom for this interaction effect was corrected using

the Greenhouse-Geisser estimates of sphericity. All statistical analyses were performed with JASP (Version 0.17.2.1, 2023).

4.4. Results

4.4.1. Strategy Use and Information Acquisition

We first calculated the percentages of choices in line with each of the two strategies, the Weighted Additive rule (WADD) and the lexicographic heuristic Take-the-best (TTB). In the compensatory environment, across all participants, trials, and stimulation sites, WADD predicted 70.64% of choices and TTB predicted 70.81%, while for the noncompensatory environment, WADD predicted 67.81% of choices, and TTB predicted 75.60%. Hence, both strategies performed better than chance (50%) in identifying participants' choices in both environments. While the strategy preference for TBB and WADD found in the noncompensatory environment was significant ($t(16) = 2.74$, $p = .01$, d = .66), in the compensatory environment was not a significant difference ($t(16) = .05$, $p = .96$, d = .01). Discriminating trials (i.e., trials where WADD and TTB made opposite predictions) in the compensatory environment comprised 33.33% (12) of all 36 trials, and in the noncompensatory environment constituted 47.22% (17) of all 36 trials. On the former, WADD predicted 47.39% of choices and TTB predicted 52.61% of choices, whereas for the latter WADD predicted 41.75% of choices and TTB predicted 58.25% of choices. Thus, TTB was better at explaining participants' choices regardless of the environment in the discriminatory trials. This is in contrast to the findings of Wichary et al. (2017), in which using a compensatory environment with 39% of discriminatory trials found that WADD predicted 60% and TTB predicted 40% of choices. However, it can be explained by the fact that we are including the strategy use after the TBS stimulation on the three sites. Another explanation may lie in the design of the task, as it provides the cues (if requested) in a decreased order of their validates, which may artificially boost the

use of TTB (Newell & Shanks, 2003). In total, across environments, and on the discriminating trials, TTB predicted 55.43% of the choices and WADD predicted 44.57% of the choices. Further, we created a single continuous variable called relative strategy preference for each participant by subtracting the percentage of choices that were consistent with TTB from the percentage of choices that were consistent with WADD (Table 1; the relative preference of WADD over TTB).

To describe participants' pre-choice behavior, their information search was measured by adding the number of cues that each participant acquired before each choice, 6 being the maximum they could acquire. A paired t-test indicated a significant difference ($t(16) = 2.27$, $p = .04$, d = .55) between the mean number of cues participants requested in the compensatory environment (M = 4.27, SD = 2.01) and in the noncompensatory environment (M = 3.76, SD = 2.01). The number of cues also significantly correlated with the relative preference for strategy in the compensatory environment (r = 0.79, $p < .001$) and in the noncompensatory environment (r = 0.51, $p = .04$). The latter correlation is consistent with the findings of Rieskamp & Hoffrage (2008) and Wichary et al. (2016), and contrary to the nonsignificant correlation found by Wichary et al. (2017) in which they used a compensatory environment for their PIT.

A paired t-test indicated a significant difference ($t(16) = 2.28$, $p = .04$, d = .55) between the mean total decision time that participants spend in the compensatory environment (M = 11.78, SD = 5.71) and in the noncompensatory environment (M = 10.39, SD = 5.53). The mean total decision time also significantly correlated with the relative preference for strategy in the compensatory environment (r = 0.83, $p < .001$) and in the noncompensatory environment (r = 0.51, $p = .04$). In contrast, Wichary et al. (2017) found a nonsignificant correlation between these two variables. The mean values and standard deviations of decision times, number of cues taken, strategy preference, and

relative strategy preference for each stimulation site, environment, and total values are reported in Table 1.

4.4.2. ANOVA Analysis

For this analysis, we averaged the dependent variables in 6 blocks of trials (each block being the average of 6 trials) to reduce their intertrial variability. We first report the results of the repeated measures ANOVA with the effects of cTBS over the rIFG, pre-SMA, and rSPL, the environment structures, and blocks of trails on the number of cues acquired, then on the decision time, and finally on the relative strategy preference.

The environment structure had a statistically significant effect on the number of cues acquired, $F(1,16) = 5.14$, $p = .04$, partial $\eta^2 = .24$. Additionally, there was a statistically marginal interaction effect between the environment structure and the blocks of trials on the number of cues acquired, $F(5,16) = 2.78$, $p = .07$, partial $\eta^2 = .15$, but no significant effect of the block of trials themselves, $F(5, 6) = 1.14$, $p = .35$, partial $\eta^2 = .07$. As shown in Figure 5, only after rIFG stimulation the difference in the mean number of cues taken in the compensatory environment (M = 4.28, SD = 2.06) and the noncompensatory environment (M = 3.34, SD = 2.02) was statistically significant ($t(44.65) = -2.86$, $p = .006$). However, the interaction effect between the stimulation sites and the environment structure on the number of cues taken was marginal ($F(2,16) = 2.67$, $p = .08$, partial $\eta^2 = .14$).

Only a statistically significant main effect of the environment structure on the decision time was observed, $F(1,16) = 5.20$, $p = .04$, partial $\eta^2 = .24$. There was a marginal statistical interaction effect between the environment structure and the blocks of trials on the decision time, $F(5,16) = 1.84$, $p = .11$, partial $\eta^2 = .10$. but no significant effect of the block of trials themselves, $F(2.77,16) = 0.88$, $p = .45$, partial $\eta^2 = .05$. As

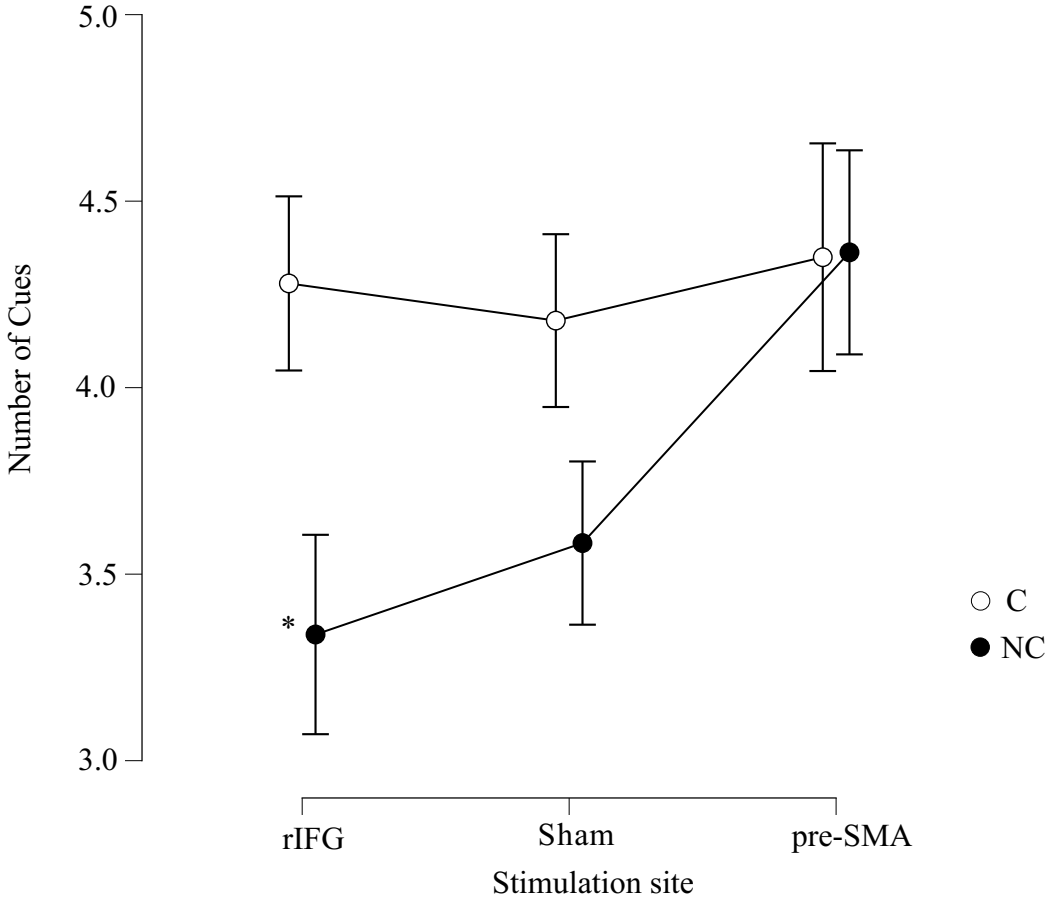
shown in Figure 6, when the rIFG was stimulated, the difference between the mean decision time in the compensatory environment (M = 11.45, SD = 5.68) and the noncompensatory environment (M = 9.91, SD = 5.34) were statistically significant (t(-44.88) = - 2.45, p = .02). However, the interaction effect between the stimulation sites and the environment structure on the decision time was not significant F(2,16) = 1.53, p = .23, partial $\eta^2 = .09$).

Finally, the environment structure had a marginally significant effect on the relative strategy preference, F(1,16) = 4.49, p = .05, partial $\eta^2 = .22$. There was also a statistically significant effect of the blocks of trails on the relative strategy preference, F(5,16) = 4.14, p = .002, partial $\eta^2 = .21$. Furthermore, a statistically significant interaction effect was found between the environment structure and the blocks of trials on the relative strategy preference, F(5,16) = 16.90, p < .001, partial $\eta^2 = .51$ (Figure 7). There was a statistically significant interaction effect between the stimulation sites, the environment structure, and the blocks of trials on the relative strategy preference, F(5,16) = 2.05, p = .03, partial $\eta^2 = .11$ (Figure 8, Figure 9, and Figure 10). However, the interaction effect between the stimulation sites and the environment structure on the relative strategy preference was not significant (F(2,16) = .18, p = .83, partial $\eta^2 = .01$). Considering the third-level interaction in the compensatory environment (Figure 11), only in block 4, participants preferred significantly less (p = .01) the TTB strategy over WADD after cTBS over pre-SMA compared to sham. In the noncompensatory environment (Figure 12) only in block 1, participants preferred significantly less (p = .002) the TTB strategy over WADD after cTBS over pre-SMA compared to sham. Additionally, in block 1, participants preferred significantly less (p = .01) the TTB strategy over WADD after cTBS over pre-SMA compared to rIFG. These significant differences in block 4 in the compensatory environment and, in block 1 in the noncompensatory environment may be

explained by the distribution of discriminatory trials. In the compensatory environment and block 4, there was the highest proportion of discriminating trials, that is, from the six trials four of them were discriminatory. This proportion (66.7%) was the highest and single one of all blocks. In the noncompensatory environment occurred the same effect but in block 1, where there was the highest proportion of discriminatory trials (five out of six, or 83,33%).

Figure 5

Number of Cues vs. Stimulation Site



Note. C = compensatory; NC = noncompensatory; rIFG = right inferior frontal gyrus; pre-SMA = pre-supplementary area. Error bars denote 95% confidence intervals. Applying cTBS over the right inferior frontal gyrus (rIFG) resulted in a significant difference in the number of cues taken between environments. Contrast tables are reported in Appendix H.

* $p = .006$

Table 1

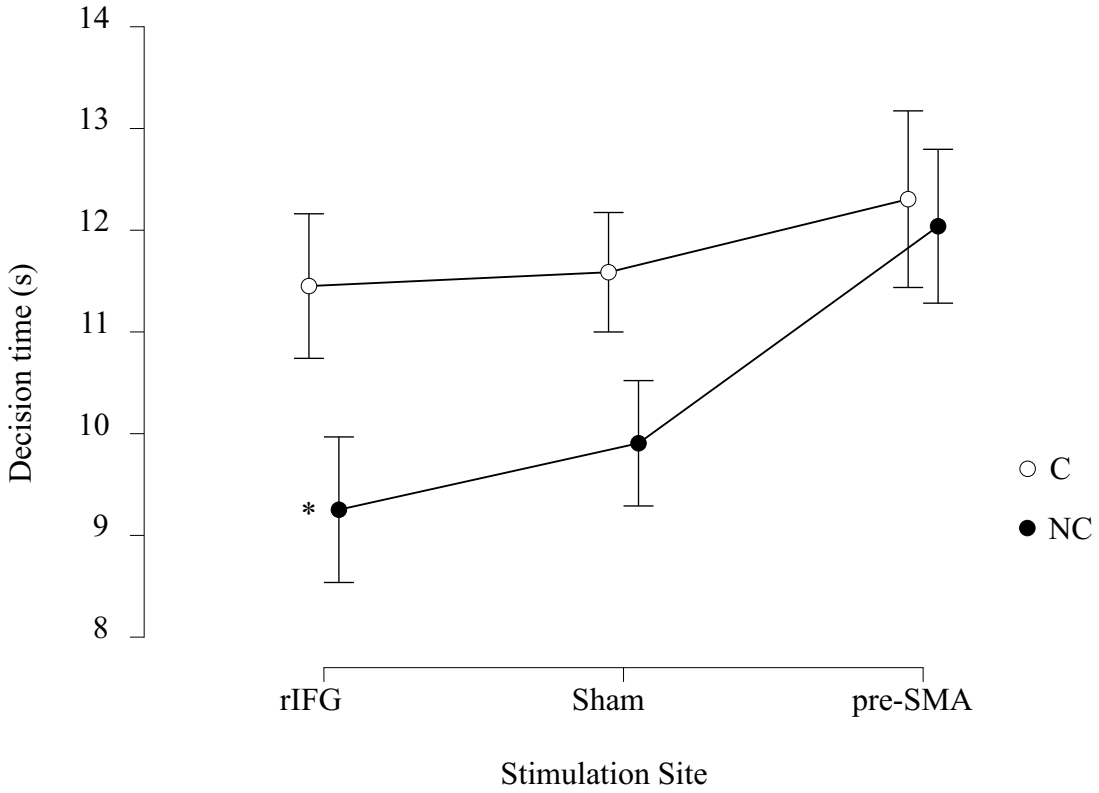
Mean Values of the Three Dependent Variables for each Environment and Stimulation Site

Environment	C			NC			rIFG	Sham	pre-SMA
Stimulation site	rIFG	Sham	pre-SMA	rIFG	Sham	pre-SMA			
Number of cues	4.28 (2.06)	4.18 (2.01)	4.35 (1.96)	3.34 (2.02)	3.58 (1.95)	4.36 (1.90)	3.81 (1.88)	3.88 (1.93)	4.36 (1.80)
Total		4.27 (2.01)			3.76 (2.01)			4.01 (1.67)	
Decision time	11.45 (5.68)	11.59 (5.68)	12.31 (5.72)	9.25 (5.49)	9.91 (5.34)	12.04 (5.36)	10.35 (5.10)	10.75 (5.42)	12.17 (5.22)
Total		11.78 (5.71)			10.39 (5.53)			11.09 (4.69)	
Strategy preference									
WADD	71.08	66.67	74.18	66.99	65.69	70.75	69.06	66.18	72.47
Total		70.64			67.81			69.22	
TTB	71.57	70.92	69.93	77.29	75.98	73.53	74.43	73.45	71.73
Total		70.80			75.60			73.20	
Relative strategy preference	-0.49	-4.25	4.25	-10.29	-10.29	-2.78	-5.39	-7.27	0.73
Total		-0.16			-7.79			-3.98	

Note. N = 17. C = compensatory; NC = noncompensatory; rIFG = right inferior frontal gyrus; pre-SMA = pre-supplementary motor area; WADD = weighted additive rule; TTB = take-the-best. All numbers in this table are the mean values of each variable. Standard deviations are in parentheses. The number of cues are represented in absolute values; Decision times are measured in seconds; and, both strategy preference variables are represented in percentages. Negative values of relative strategy preference indicate a preference for the TTB heuristic and positive values indicate a preference for the WADD rule.

Figure 6

Decision Time vs. Stimulation Site

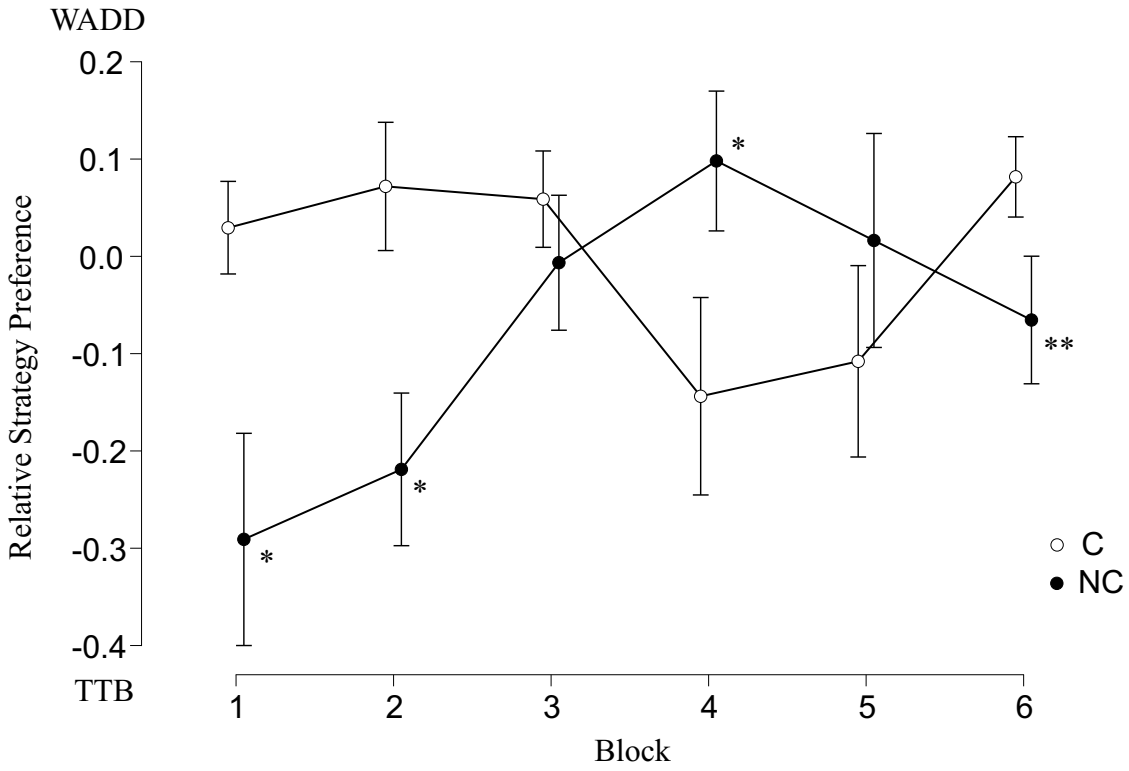


Note. C = compensatory; NC = noncompensatory; rIFG = right inferior frontal gyrus; pre-SMA = pre-supplementary area. Error bars denote 95% confidence intervals. Applying cTBS over the right inferior frontal gyrus (rIFG) resulted in a significant difference in the decision time between environments. Contrast tables are reported in Appendix I.

* $p = .02$

Figure 7

Relative Strategy Preference vs. Block



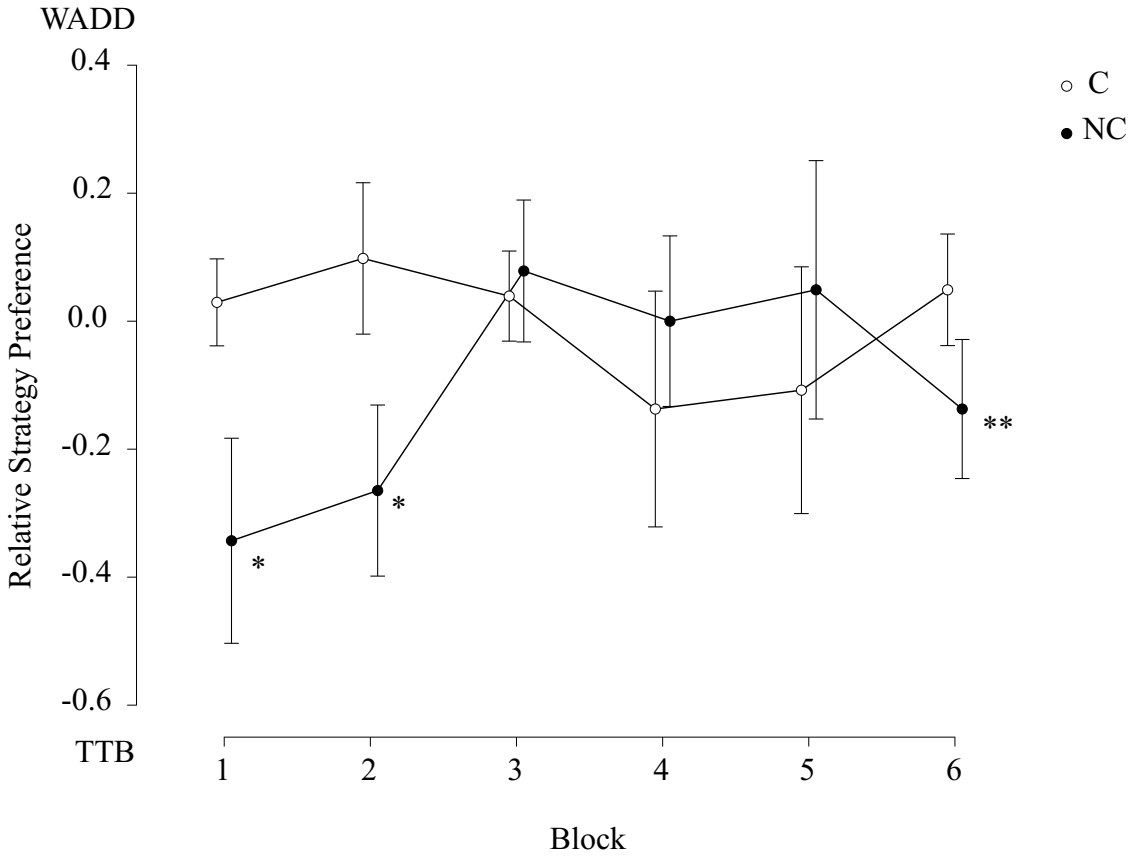
Note. C = compensatory; NC = noncompensatory; TTB = Take-the-Best; WADD = weighted additive. Error bars denote 95% confidence intervals. Relative Strategy Preference is expressed in percentage. The Relative Strategy Preference for TTB over WADD between environment structures was statistically significant for blocks 1, 2, 4, and 6. Contrast tables are reported in Appendix J.

* $p < .001$

** $p = .02$

Figure 8

Relative Strategy Preference after rIFG Stimulation vs. Block



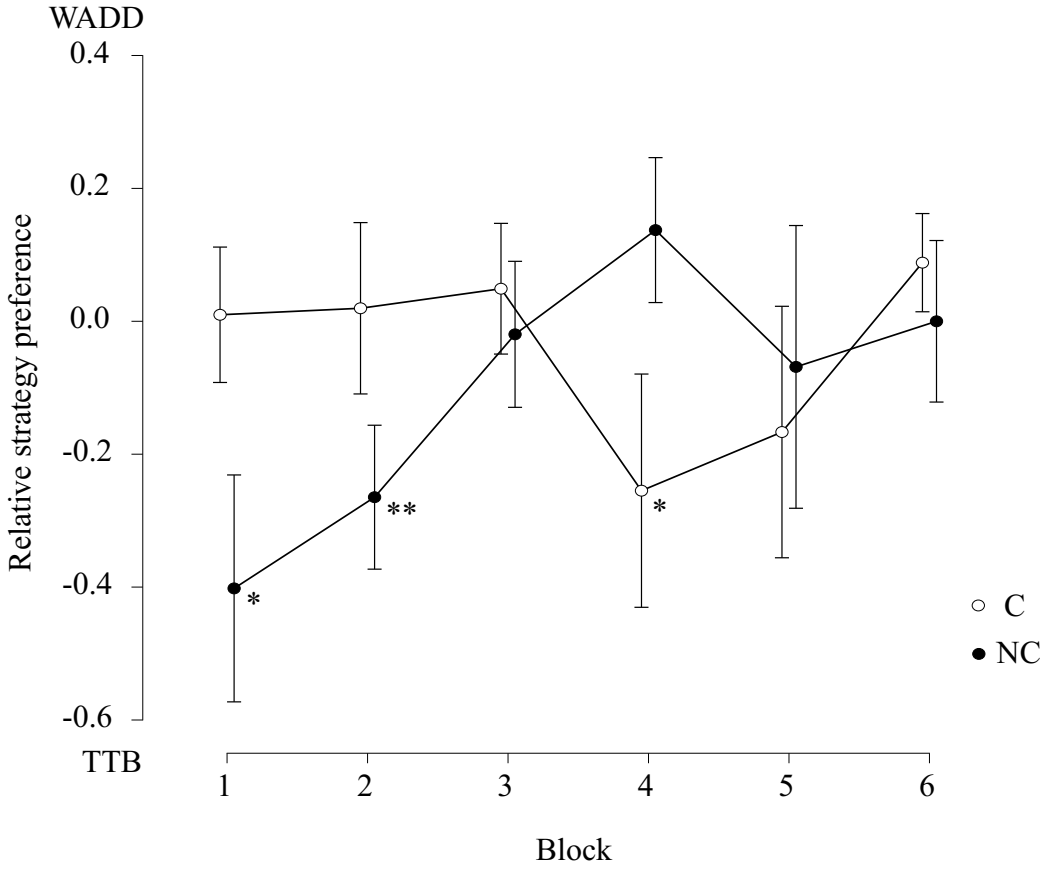
Note. rIFG = right inferior frontal gyrus; C = compensatory; NC = noncompensatory; TTB = Take-the-Best; WADD = weighted additive. Error bars denote 95% confidence intervals. Relative Strategy Preference is expressed in percentage. The Relative Strategy Preference for TTB over WADD between environment structures was statistically significant for blocks 1, 2, and 6. Contrast tables are reported in Appendix K.

* $p < .001$

** $p = .04$

Figure 9

Relative Strategy Preference after Sham Stimulation vs. Block



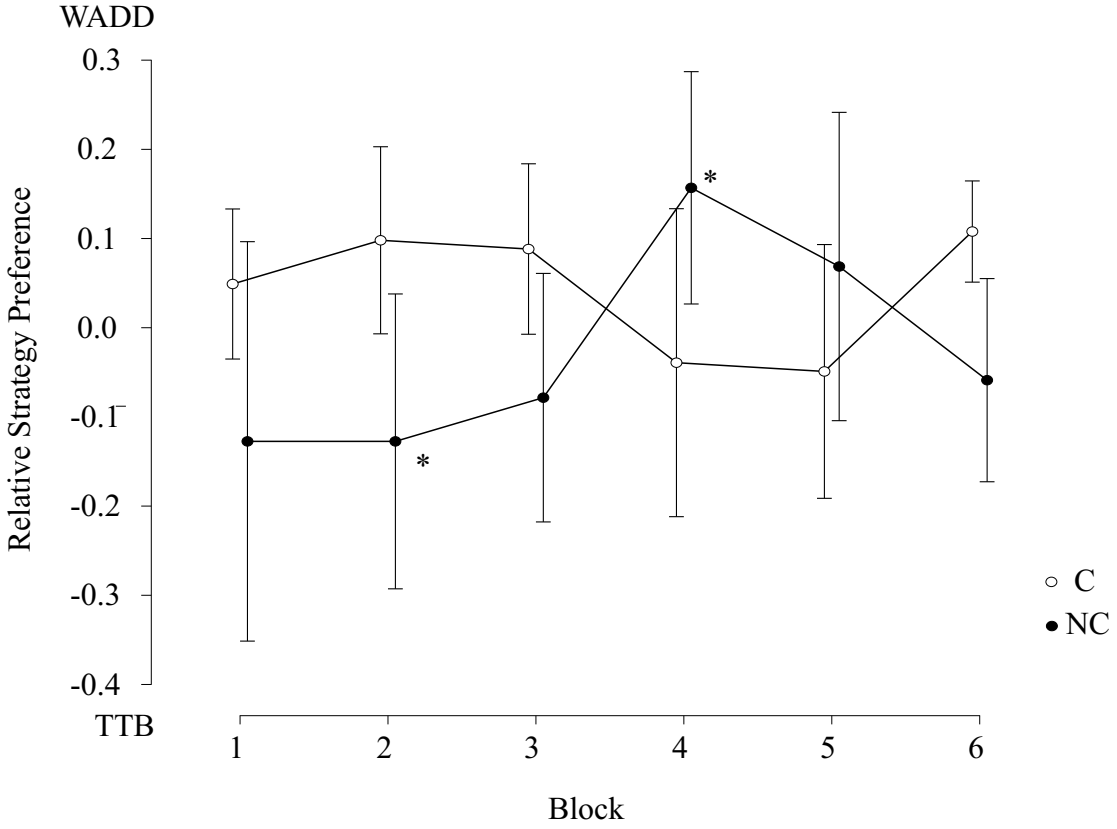
Note. C = compensatory; NC = noncompensatory; TTB = Take-the-Best; WADD = weighted additive. Error bars denote 95% confidence intervals. Relative Strategy Preference is expressed in percentage. The Relative Strategy Preference for TTB over WADD between environment structures was statistically significant for blocks 1, 2, and 4. Contrast tables are reported in Appendix L.

* $p < .001$

** $p = .002$

Figure 10

Relative Strategy Preference after pre-SMA Stimulation vs. Block



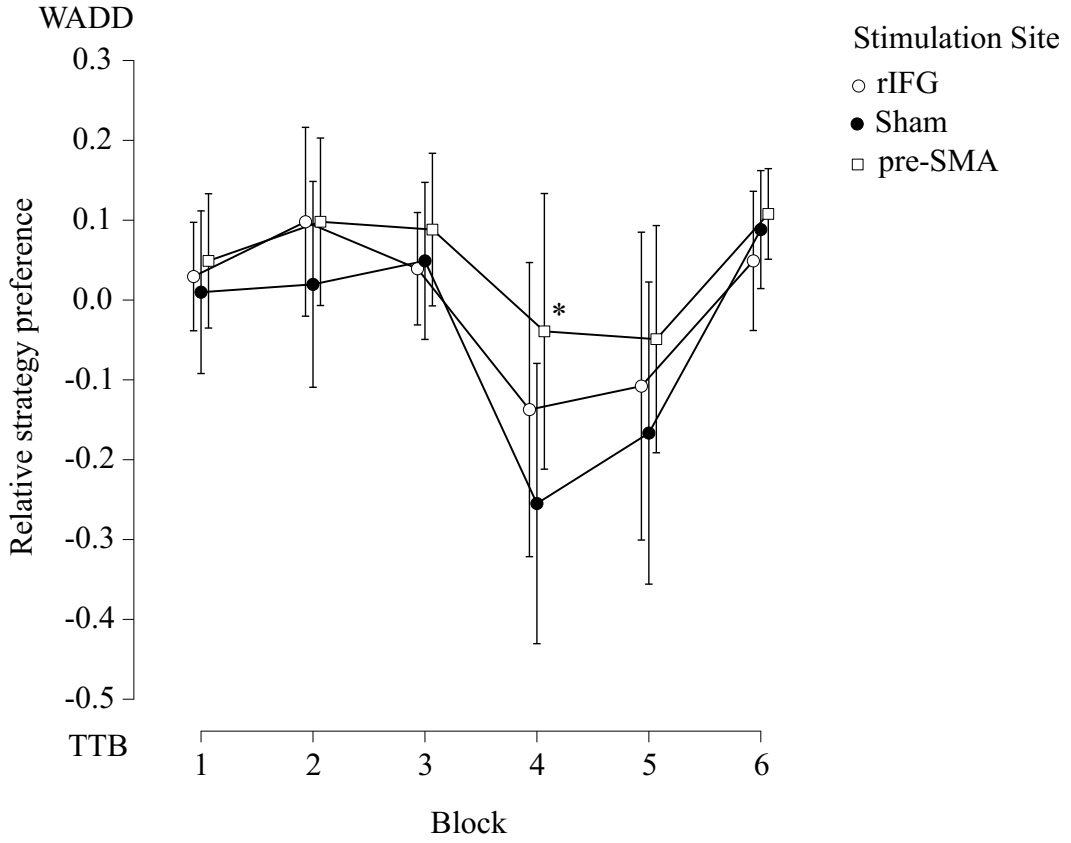
Note. pre-SMA = pre-supplementary motor area; C = compensatory; NC = noncompensatory; TTB = Take-the-Best; WADD = weighted additive. Error bars denote 95% confidence intervals. Relative Strategy Preference is expressed in percentage. The Relative Strategy Preference for TTB over WADD between environment structures was statistically significant for blocks 2 and 4. Contrast tables are reported in Appendix M.

* $p = .01$

** $p = .03$

Figure 11

Relative Strategy Preference vs. Block in the Compensatory Environment

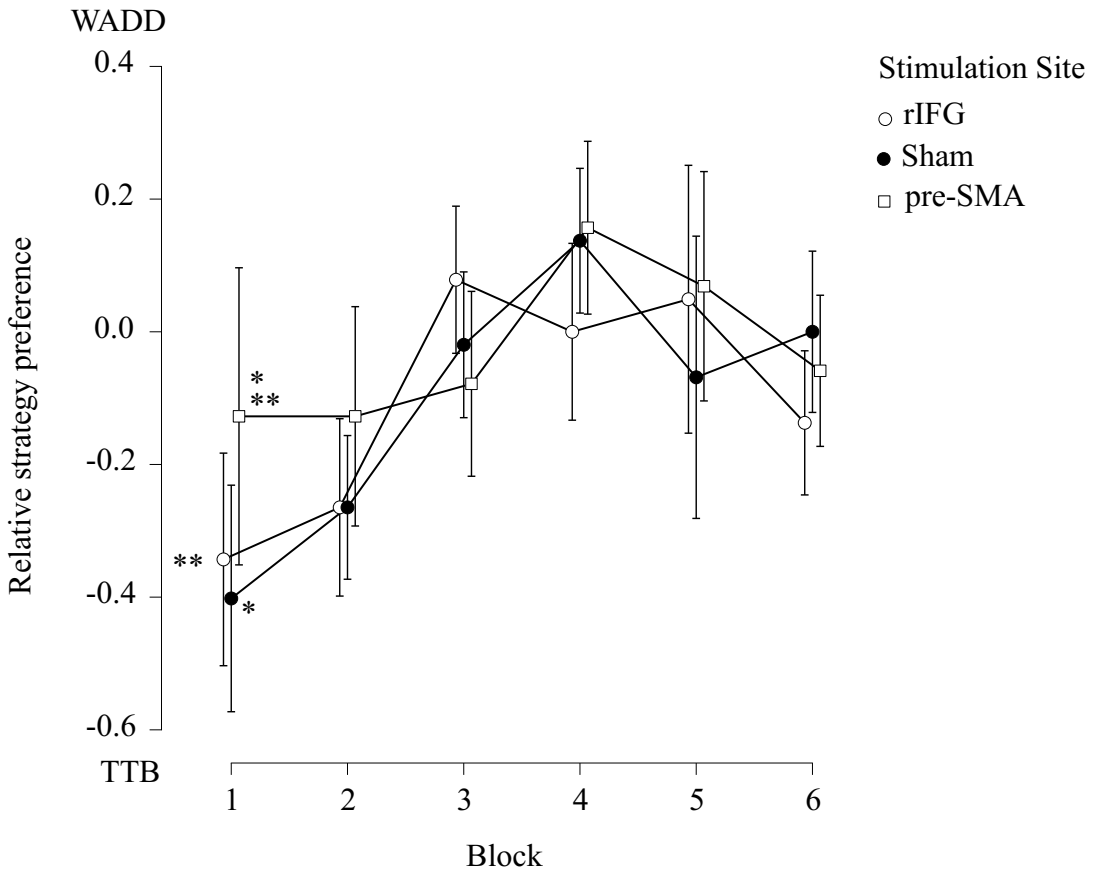


Note. rIFG = right inferior frontal gyrus; pre-SMA = pre-supplementary motor area; TTB = Take-the-Best; WADD = weighted additive. Error bars denote 95% confidence intervals. Relative Strategy Preference is expressed in percentage. There was a statistically significant lower Relative Strategy Preference for TTB over WADD in block 4 after pre-SMA stimulation compared to sham.

* $p = .01$

Figure 12

Relative Strategy Preference vs. Block in the Noncompensatory Environment



Note. rIFG = right inferior frontal gyrus; pre-SMA = pre-supplementary motor area; TTB = Take-the-Best; WADD = weighted additive. Error bars denote 95% confidence intervals. Relative Strategy Preference is expressed in percentage. There was a statistically significant lower Relative Strategy Preference for TTB over WADD in block 1 after pre-SMA stimulation compared to sham and rIFG.

* $p = .002$

** $p = .01$

4.5. Discussion

In the present study, we used cTBS to investigate the causal role of inhibition and its neural basis in multi-attribute decision-making in healthy individuals. The multiattribute decision strategy task aimed to capture the strategies that participants used in a compensatory and noncompensatory environment after cTBS was delivered in three conditions: rIFG, sham to rSPL, and pre-SMA. Based on our literature review, this research appears to be the only study that has focused on the combination of these topics and methodology. Overall, across stimulation sites, environments, and trials, participants' strategy use was better described by the simple one-reason decision-making heuristic TTB. However, other participants chose to integrate the given information using WADD. While inhibiting the rIFG did not lead to any significant change in what strategies the participants preferred, inhibiting pre-SMA caused their behavior to integrate more information compared to inhibiting the rSPL (sham) in block 4 where the proportion of discriminatory trials was the highest. These findings are discussed in detail in the next paragraphs.

Regarding participants' pre-choice behavior, we found a significant difference in the average number of cues taken and decision time between the noncompensatory environment and the compensatory environment across stimulation sites and trials (Figure 5 & Figure 6). On one hand, participants acquired fewer cues and spent less time deciding in the noncompensatory environment compared to the compensatory environment across trials. This relation replicated as well in the sham condition in both environments. Further, participants who acquired fewer cues and spent less time across trials had a higher relative preference for TTB over WADD in the noncompensatory environment. This high preference for TTB over WADD was also found in the discriminatory trials of the noncompensatory and compensatory environment. The findings on the noncompensatory

environment support our first hypothesis. Consistent with the adaptive decision-maker hypothesis of Payne et al. (1988) and the adaptive toolbox approach of Gigerenzer (1997) and Gigerenzer et al. (1999), participants chose their strategies adaptively to the environment. Hence, TTB was a successful strategy to draw inferences in the designed noncompensatory environment as there was a fit between the structure of the noncompensatory TTB strategy and the environment. Our results also relate to the theorem three on noncompensatory information of Martignon & Hoffrage (2002), which states that "The performance of Take The Best is equivalent to that of a linear model with a noncompensatory set of weights" (p. 47). Also, it indicates that WADD can never outperform TTB in this type of environment and with cues ordered by decreasing validity as in our design (Martignon & Hoffrage, 1999). On the empirical side, our findings are similar to those of Bröder (2000; Experiment 3), in which a higher proportion of participants preferred TTB over WADD in a noncompensatory environment (65%) compared to the compensatory environment (40%). As in our PIT, the information in their task was acquired successively, participants received feedback on their decisions, and they had both environment structures: a noncompensatory structure that favored TTB over WADD, and another compensatory environment that favored WADD rule over TTB heuristic. The same direction on strategy preference was found by Bröder (2003; Experiment 1) with the difference that cue values were hidden, but participants also received feedback on their decisions. In another study by Newell & Shranks (2003; Experiment 3), they found that 75% of the participants preferred TBB over WADD in a task designed to favor TBB. However, the results of the two last studies are not fully comparable to ours as their task design differs from ours.

On the other hand, participants acquired more cues and spent more time deciding in the compensatory environment compared to the noncompensatory environment across

trials. Thus, as participants acquired more cues, they spent more time in this actioning (accumulating evidence before selecting an option) and computing the weighted value, which ultimately led them to employ the WADD strategy more than TTB. Contrary to our first hypothesis and upon closer analysis, participants' strategy preference was on average slightly higher for TTB over WADD (difference of 0.16%) in the compensatory environment as well. This relationship was found to replicate when considering the strategy preference in the sham condition (Table 1) and the discriminatory trials of this environment. These results are similar to those of Wichary et al. (2016) in which they found that participants who were emotionally stressed preferred simpler strategies when making inferences, supporting the attentional-narrowing hypothesis (increased anxiety leads to reduced information processing). Similar to our method, they also used a PIT with a compensatory environment. Although we did not induce stress in participants during the procedure or used their reported arousal and state and trait anxiety levels during these analyses, it could be valuable to investigate this relationship further as our results may be explained by this same attentional-narrowing hypothesis. In contrast, Wichary et al. (2017) used a PIT with a compensatory environment in which participants' arousal levels were not manipulated and found that WADD predicted 60% and TTB predicted 40% of their choices. Additionally, in a similar task design, Bröder (2000; Experiment 3) found that a higher proportion of participants preferred WADD over TTB in the compensatory environment (60%) compared to the noncompensatory environment (35%). In other terms, our results in the compensatory environment may be due to individual differences such as arousal levels and anxiety levels, suggesting that contrary to what Payne et al. (1988) sustain; strategy selection is not perfectly adaptive but it also depends on idiosyncratic preferences towards these strategies (Bröder, 2000). Another possible explanation for our results may be in part due to what Newell & Shanks (2003)

raised in their study: The task provides the cues (if requested) in a decreased order of their validates, which may artificially boost the use of TTB. Nevertheless, from another point of view, the strategy preference for WADD increased in the compensatory environment compared to the noncompensatory environment, which led to an almost equal preference for WADD and TBB in this environment. Our results in the compensatory environment allow a double interpretation. First, following the adaptive decision-maker hypothesis of Payne et al. (1988) and the adaptive toolbox perspective of Gigerenzer and colleagues (1999), some participants still adaptively choose the WADD strategy over TTB in the compensatory environment more than in the noncompensatory environment. Second, the almost equal strategy preference for TTB over WADD still shows that some participants choose a one-reason decision-making heuristic to resolve their decisions. One theoretical explanation could be as Payne et al. (1998) highlighted that sometimes individuals use heuristics that lead to decision errors which may reflect a trade-off between cognitive effort and accuracy. Alternatively, Simon (1981) states that the decision-maker is often a satisficer, in the sense that they do not have other options in some decision environments than the use of heuristics because they are unsure of the alternatives ahead of time (Gigerenzer & Todd, 1999). It remains to be clarified in future research if this is due to individual differences, task design, or error.

Altogether, these results partially support our first hypothesis, participants' choices were better explained by TTB over WADD in the noncompensatory environment but WADD did not explain better than TTB in the compensatory environment. Nevertheless, decision-makers' strategies were still better explained by TTB over WADD in the compensatory environment, and overall their relative strategy preference was not consistent with the environment structure. Although this strategy preference found in the compensatory environment challenges the adaptive decision-maker hypothesis (Payne et

al., 1988), is important to highlight that it was not a significant difference. Moreover, in this environment, participants almost equally preferred TTB and WADD, suggesting that participants' strategy preference behavior was almost equally explained by one-reason decision-making and weighted additive rule strategies. This may reflect the existence of inter-individual differences in participants' strategy preference determined by idiosyncratic preferences (Bröder, 2000).

We also found that our results partially align with our second hypothesis: The environment structure had a significant impact only on the number of cues and decision time, whereas further investigation on the marginal effect on the relative strategy preference is needed. Interestingly, the marginal interaction effect of the environment structure and the stimulation site on the number of cues and decision time was found in a different direction from what was expected. Only after stimulation over the rIFG the difference in the number of cues acquired by participants and the allocated decision time they spent in between the compensatory and noncompensatory environment was significant (also true for decision time; Figure 5 & Figure 6). This may suggest that inhibiting rIFG may enhance participants' pre-choice behavior to the environment of the task as if their adaptiveness to the environment was improved. Furthermore, although in the noncompensatory environment, after inhibiting rIFG compared to sham participants acquired fewer cues and spent less time on their decision, this effect was not significant. Additionally, and contrary to our hypothesis, inhibiting rIFG did not produce any significant change in the relative strategy preference compared to sham in any block. In the same direction, the participant's relative strategy preference was adapted to the environment after inhibiting rIFG in blocks 1, 2, and 6. Although the evidence of the inhibitory role of the rIFG (Aron et al., 2003, 2004, 2014) may help to explain these results on blocks 1, 2, and 6 for the noncompensatory environment, that is inhibiting rIFG

suppressed its inhibitory function, the same explanation does not hold for the compensatory environment. Together with the non-significant increase in the number of cues and decision time compared to sham in the compensatory environment, it may indicate that the rIFG is more plausible to be a component of other cognitive domains than to be a unique module for inhibition (Dippel & Best, 2015; Erika-Florence et al., 2014; Hampshire et al., 2010) in multiattribute decision tasks. It may be the case as other studies suggest that the rIFG is a center that hosts subregions of various functional networks (Hampshire, 2015; Hampshire & Sharp, 2015a; Hampshire & Sharp, 2015b) that respond differently depending on the type of cognitive demand.

As for our third hypothesis, we found the opposite to be the case. After inhibiting pre-SMA, participants acquired a higher number of cues and spent more time on their decisions compared to sham in both environments, although this difference was not significant (Figure 5 & Figure 6). The environment structures and the stimulation site were not significantly associated with the relative strategy preference in opposition to what we expected, therefore it was not possible to differentiate participants' relative strategy preference based on only these two independent variables separately to test part of our second and third hypotheses. Nevertheless, when looking at the two-level interaction effect between the number of blocks and the environment on the relative strategy preference (Figure 7), participants' relative strategy preference was adapted to the environment in blocks 1, 2, and 6. In these, they significantly preferred TTB over WADD in the noncompensatory environment and significantly preferred WADD over TTB in the compensatory environment. These results may be additional evidence in favor of the adaptive decision-maker hypothesis of Payne et al. (1988) and the adaptive toolbox perspective of Gigerenzer and colleagues (1999). Furthermore, the significant change in the relative strategy preference in block 4 may be partially explained by the fact that

participants changed their strategies due to time pressure (Payne et al., 1988), part of an exploratory behavior or related to the sudden change in the proportion of discriminatory trials per block. Although time was not a variable introduced in the task's instructions or verbally communicated to the participants, the instruction of the strop-task did contain these terms which could have produced an interference effect on the decision task. However, as they received further feedback on their decisions they came back to those adapted to the environment (block 6) suggesting a learning effect following the strategy selection learning hypothesis of Rieskamp & Otto (2006). Accordingly, individuals selected strategies based on their expectations and then were updated according to the experience that followed. Continuing in the compensatory environment (Figure 11), we observed that participants followed almost the same pattern in their relative strategy preference fluctuations throughout the blocks of trials. Interestingly, inhibiting pre-SMA led participants to use less TBB over WADD compared to sham in block 4, although the relative strategy preference was still in favor of TBB over WADD. In other words, inhibiting pre-SMA significantly modulated what strategies the participants chose. This may suggest that inhibiting pre-SMA led to an increase in the decision threshold of evidence (feedback) needed to employ TTB over WADD to make inferences. Thus, this result is in accordance with those from Tosun et al. (2017) and Berkay et al. (2018), in which they found that cTBS over pre-SMA led to an increase in the decision threshold in the decision tasks. That is, our findings support the premise that pre-SMA plays a significant role in the preparatory selection and modulation of decision thresholds (Georgiev et al., 2016; Ikeda et al., 1999; Nachev et al., 2007; Shima et al., 1996), while the same significance may not hold for its role in the inhibitory network (Chen et al., 2009; Floden & Stuss, 2006; Picton et al., 2007). Taking this result one step further, it provides causal evidence of the relationship between pre-SMA and the globus pallidus

via striatum during response inhibition, which is in favor of the striatal theory. Further, among the inhibitory pathways covered, our results in this section support that the short indirect pathway is causally involved in multiattribute decision-making. In contrast, this result differs from those that provide evidence of a "hold your horses" pause function of pre-SMA through the hyperdirect pathway when conflictive decisions are detected (subthalamic theory; Aron & Poldrack, 2006; Aron et al., 2016; Bogacz & Gurney, 2007; Hannah & Aron, 2021; Wiecki & Frank, 2013). Under this view, inhibiting pre-SMA should have led to a decrease in the decision thresholds, facilitating the relative strategy preference for TTB over WADD. This is because the lower activity of pre-SMA would have led to STN to decrease GPi's inhibition of the thalamus, facilitating the direct pathway to fire without the pause imposed by the STN through the hyperdirect pathway.

Among the limitations of our study, the sample size and power analysis are the main ones. Although some studies suggest that 13 participants are the minimum necessary to detect behavioral effects of TMS (Sack et al., 2009), the calculations for the sample size with the software G*Power (Faul et al., 2009) needed to run the reported ANOVA analyses with a power analysis (1-β) of 0.95 indicated a minimum of 45 participants. With our current sample size of N = 17, our power analysis is below 0.6, which may explain the null effects after rIFG stimulation in dependent variables mostly compared to sham, and other nonsignificant results we reported here. Similarly to the study of Berkay et al. (2018), they administered iTBS or cTBS over pre-SMA, and a sham condition in a counterbalanced order and had a sample of N = 17 participants. In contrast, the study of Tosun et al. (2017), had a sample of N = 24 participants total (12 for the pre-SMA condition and 12 for the sham condition). Another TMS study conducted by Tsujii et al. (2011), assigned 24 participants to each of the two stimulation sites (total of N = 48). Consequently, our sample size is debatable compared to other studies with a similar

design, nevertheless, without the power analysis needed to detect reliable effects, our results are limited in their generalizability.

In conclusion, we provide preliminary evidence that in a multiattribute decision-making task participants relatively preferred TTB over WADD in both environments and its discriminatory trials as well. This means that in the noncompensatory environment, participants chose adaptively to the environment in line with the adaptive decision-maker hypothesis of Payne et al. (1988) and the adaptive toolbox approach of Gigerenzer (1997) and Gigerenzer et al. (1999). As for the compensatory environment, further investigation is needed using the results of the STAI, BIS-11, and NFCC-SF to corroborate if this effect was related to any of those measures or if there are other possible explanations such as the task design or is due to the sample size, among others. Additionally, our study provides causal evidence that during a multiattribute decision task, the rIFG does not play a significant inhibitory role. After inhibiting rIFG, participants' relative strategy preference did not significantly change in any direction compared to sham. This may be an indication that the rIFG is a cortical hub for other cognitive functions than just only inhibition, and its inhibitory function may depend on the type of cognitive task or demand being processed by the brain. This hypothesis needs to be corroborated with the final sample of the study that is currently ongoing. On the role of pre-SMA, we found that it served as a modulatory center of decision thresholds in the multiattribute decision tasks. After inhibiting pre-SMA, participants needed a higher cue threshold compared to sham, which led them to use less TTB and more WADD. However, this effect was only present in block 4 in the noncompensatory environment and in block 1 in the compensatory environment, where there was the maximum proportion of discriminatory trials in each of them. Nonetheless, participants relatively preferred TBB over WADD in these two blocks. The finding on the role of pre-SMA builds up on the causal evidence in favor of

the striatal theory and the short indirect pathway of the basal ganglia networks for inhibitory control during decision-making tasks. Further research is needed using a similar design with two tasks (a stop-signal task and a multiattribute decision-making task) together with iTBS and cTBS to corroborate the neural substrate of the inhibitory network both at a cortical and subcortical level.

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Appendix

Appendix A

A2. BROSZURA INFORMACYJNA DLA UCZESTNIKÓW BADANIA

dotycząca badania podejmowania decyzji z użyciem przezczaszkowej stymulacji magnetycznej (TMS) w ramach grantu OPUS (2019/35/B/HS6/01173)

Badanie:

Źródła racjonalności: Rola procesów hamowania i ich neuronalnego podłoża w stosowaniu strategii decyzyjnych

Proszę uważnie *zapoznać się z poniższymi informacjami przed decyzją o wzięciu udziału w badaniu. W razie niejasności proszę zadawać pytania, a osoby prowadzące badanie wytłumaczą w przystępny sposób przebieg całego badania.*

Cel badania:

Celem badania jest określenie, w jaki sposób mózg ludzki pracuje podczas podejmowania skomplikowanych, wieloetapowych decyzji. Odpowiedzi na to pytanie dostarczy przezczaszkowa stymulacja mózgu (TMS) oraz obrazowanie mózgu metodą rezonansu magnetycznego (MRI). Podczas użycia każdej z tych metod będzie Pani/Pan wykonywać dwa zadania. Zostały one opisane w dalszej części tej broszury oraz zostaną dokładniej zaprezentowane przez osobę prowadzącą badanie w formie ustnej oraz w formie procedury treningowej umożliwiającej wstępne zapoznanie się z zadaniem.

Ogólne informacje o TMS:

TMS (ang. *Transcranial Magnetic Stimulation*) – przezczaszkowa stymulacja magnetyczna jest techniką umożliwiającą stymulację mózgu z zewnątrz głowy. Podczas badania TMS generator pola magnetycznego, czyli "cewka", jest umieszczany w pobliżu głowy osoby poddawanej zabiegowi. Cewka wytwarza niskie prądy elektryczne w obszarze mózgu tuż pod cewką poprzez indukcję elektromagnetyczną. Na przykład, gdy cewka jest trzymana nad obszarem mózgu, który kontroluje rękę, stymulacja może spowodować drganie ręki. TMS jest stosowany zarówno do celów klinicznych, jak i naukowych od 1985 roku. W szpitalu TMS jest stosowany na przykład do diagnozowania funkcjonowania nerwów u pacjentów ze stwardnieniem rozsianym. W neurobiologii TMS jest ważną techniką badania funkcji i połączeń obszarów mózgu. TMS może mieć bezpośredni efekt stymulacyjny, na przykład jak opisano powyżej, gdy wywoływany jest niewielki ruch palca. Impuls TMS może jednak również nieznacznie zaburzać funkcjonowanie obszaru mózgu na krótką chwilę (mniej niż sekundę). Te niewielkie perturbacje mogą być mierzone za pomocą czułego zadania behawioralnego lub innej techniki neuroobrazowania, takiej jak fMRI lub EEG.

Jeśli wiele impulsów jest dostarczanych w sposób powtarzalny, na przykład 600 w określonym wzorze, efekt TMS może utrzymywać się dłużej, w niektórych przypadkach nawet do godziny po zakończeniu stymulacji.

Przygotowanie do badania:

Ze względu na pole magnetyczne indukowane przez TMS zalecamy, aby w dniu eksperymentu nie nosić przy sobie żadnych metalowych przedmiotów. Zawsze przed stymulacją przezczaszkową należy usunąć z głowy wszystkie metalowe przedmioty (spinki do włosów, kolczyki, itp.) oraz wszystkie inne przedmioty wrażliwe na pole magnetyczne z okolicy ciała (np. telefony komórkowe, karty bankowe lub kredytowe, klucze itp.) Na noc przed dniem badania powinna Pani/Pan się normalnie wyspać. Proszę nie spożywać żadnych substancji psychoaktywnych (w tym alkoholu, z wyjątkiem kawy) w ciągu 24 godzin przed eksperymentem. Jeśli spożywa Pani/Pan kawę, proszę upewnić się, że jest to taka sama ilość, jak w każdym innym dniu, przed dniem udziału w badaniu.

Udział w badaniu:

Każda osoba wyrażająca chęć wzięcia udziału w badaniu powinna zapoznać się z broszurą informacyjną oraz podpisać formularz świadomej zgody na udział w badaniu, zgodę na przetwarzanie danych osobowych oraz kwestionariusz na temat stanu zdrowia i innych aspektów bezpieczeństwa związanych z TMS. Na podstawie udzielonych przez Panią/Pana odpowiedzi badacz zdecyduje, czy może Pani/Pan wziąć udział w eksperymencie.

Kryteria wykluczenia z badania TMS:

NIE może Pani/Pan wziąć udziału w eksperymencie TMS, jeśli dotyczy Pani/Pana jedna z poniższych sytuacji:

- wiek poniżej 18 lat
- jest Pani w ciąży lub podejrzewa Pani, że jest w ciąży
- ma Pan/Pani lub miał/a Pan/Pani poważny uraz głowy, uszkodzenie lub operację mózgu
- ma Pan/Pani aktywny implant, np. rozrusznik serca, pompę insulinową, neurostymulator
- ma Pan/Pani lub miał/a Pan/Pani epilepsję, drgawki lub napady drgawkowe
- ma Pan/Pani lub miał/a Pan/Pani w głowie duże lub ferromagnetyczne części metalowe (z wyjątkiem drutu dentystycznego)
- cierpi Pan/Pani na chorobę neurologiczną lub psychiatryczną (w tym silne bóle głowy)
- miał/a Pan/Pani kiedykolwiek omdlenia.

Przebieg eksperymentu:

Badanie składa się z dwóch zadań komputerowych oraz wypełnienia kilku kwestionariuszy. Zostanie Pani/Pan poinstruowana/-y odnośnie zadań, które będzie Pani/Pan wykonywać podczas badania. Została przygotowana specjalna procedura treningowa umożliwiająca zapoznanie się z zadaniami eksperymentalnymi i w razie wątpliwości zadanie pytań osobie przeprowadzającej badanie.

Przed rozpoczęciem eksperymentu zostanie Pani/Pan poproszona/-y o wypełnienie formularzy wymienionych powyżej w punkcie „Udział w badaniu".

Na początku badania badacz wywoła reakcje motoryczne ręki za pomocą TMS, w celu określenia indywidualnej intensywności stymulacji, która zostanie użyta do stymulacji określonym wzorcem (Theta Burst Stimulation - TBS) we właściwym eksperymencie badawczym. Prowadzący badanie upewni się również, czy dobrze toleruje Pani/Pan protokół TBS w przedniej części skóry głowy, ponieważ czasami ten rodzaj stymulacji wywołuje nieprzyjemne odczucia, spowodowane pobudzeniem mięśni czoła.

Na podstawie Pani/Pana reakcji na kilka impulsów TBS, badacz zdecyduje, czy może Pani/Pan brać udział w kolejnych częściach eksperymentu. Po zastosowanej stymulacji TMS będzie miał Pani/Pan do wykonania dwa zadania komputerowe, które pojawią się na ekranie komputera.

Podczas stymulacji TMS uczestnicy otrzymają zatyczki do uszu w celu ochrony przed hałasem stymulatora oraz usiądą w wygodnym fotelu z głową ustabilizowaną przez podpórkę pod czoło i podbródek celem minimalizacji ewentualnego dyskomfortu.

Pierwsze zadanie będzie polegało na naciskaniu przycisku po lewej lub po prawej stronie w zależności od kierunku wyświetlonej strzałki. W niektórych próbach może pojawić się dźwięk, który oznacza, że należy wstrzymać się od naciśnięcia przycisku. Czas trwania tego zadania to ok. 15 minut.

Drugie zadanie polega na podejmowaniu decyzji, co do wartości hipotetycznych diamentów. Za pomocą przycisków będzie można prosić o wskazówkę mówiącą o atrybutach diamentów lub zdecydować by wybrać jeden z dwóch diamentów. Czas trwania tego zadania to około 30 minut.

Całe badanie potrwa około 60 minut. Po skończonym badaniu, zostanie Pani/ Pan poproszona/- y o wypełnienie trzech kwestionariuszy psychologicznych, w osobnym pokoju. Nie ma limitu czasu na wypełnienie tych kwestionariuszy, zajmie to mniej więcej 15 mimnut.

W każdej chwili może Pani/Pan przerwać badanie lub zadeklarować, że nie chce Pani/Pan kontynuować badania, bez podawania przyczyny. Podczas badania TMS będzie Pani/Pan mogła ustnie poinformować o takiej chęci. Na każdym etapie badania badacze będą pytali o Pani/Pana samopoczucie i chęć kontynuacji badania.

Wynagrodzenie za udział w badaniu:

Całe badanie TMS potrwa około 6 godzin (3 sesje TMS po 2 godziny każda, sesje oddzielone będą od siebie kilkudniowymi odstępami). Za udział w badaniu z użyciem TMS przewidziana jest kwota 600 zł (stawka godzinowa 50 zł/godz.). W zależności od uzyskanego wyniku w zadaniu możliwe jest uzyskanie dodatkowe wynagrodzenia, maks. do 50 zł. W przypadku przerwania badania zostanie wypłacona kwota 100 zł za czas poświęcony w badaniu, ale musi być on nie krótszy niż godzina.

Informacje dotyczące bezpieczeństwa:

Ryzyko związane z udziałem w badaniu TMS można uznać za nieistotne lub minimalne. Badacze są przeszkoleni, a używany sprzęt spełnia międzynarodowe standardy bezpieczeństwa. Impuls TMS można usłyszeć jako kliknięcie i ewentualnie można poczuć, że mięśnie i nerwy głowy są stymulowane. Najczęstszym efektem ubocznym jest przemijający ból głowy (2-4%), który jest krótkotrwały i dobrze reaguje na lekkie środki przeciwbólowe, takie jak paracetamol. Silny ból głowy jest rzadki (0,3-0,5%). W badaniach TMS prowadzonych na populacjach pacjentów (np. z padaczką) lub wykraczających poza standardowe protokoły, w rzadkich przypadkach odnotowano napady padaczkowe. Ponadto, pola magnetyczne indukowane przez TMS oddziałują na metalowe przedmioty i urządzenia elektryczne znajdujące się w pobliżu cewki, dlatego też ich obecność w polu magnetycznym może być przyczyną zaburzeń cewki, dlatego należy wykluczyć ich obecność.

Komunikowanie problemów podczas badania TMS:

Udział w badaniu jest dobrowolny i w każdej chwili może Pani/Pan przerwać badanie bez podania przyczyny. Jest to możliwe poprzez zakomunikowanie badaczowi prowadzącemu badanie poprzez podniesienie ręki. Również wszelkie obserwacje i problemy związane z badaniem można przekazać w formie mailowej lub telefonicznej kierownikowi badania (dane kontaktowe u dołu broszury).

Co stanie się z zebranymi danymi?

Uzyskane od Państwa dane będą pseudonimizowane (tzn. nadany zostanie im kod numeryczny zamiast imienia i nazwiska). Dane będą przechowywane na komputerach i nośnikach będących własnością Uniwersytetu Jagiellońskiego. Dokument z danymi osobowymi opatrzonymi kodem numerycznym będzie przechowywany w zamkniętej na klucz szafie metalowej w gabinecie kierownika projektu i przechowywane przez 5 lat od zakończenia projektu, po czym zostaną zniszczone.

Do dalszych etapów przetwarzania, dane zostaną dodatkowo zanonimizowane, tzn. Państwa

„pseudonim” (kod numeryczny nadany w badaniu) zostanie zastąpiony losowo wygenerowanym kodem numerycznym, który nie będzie powiązany z żadnymi danymi

osobowymi, co uniemożliwi Państwa identyfikację. Tak przygotowane dane będę używane do analiz statystycznych i mogą zostać udostępnione innym grupom badawczym.

Szczegółowe informacje o ochronie danych osobowych znajdują się w klauzuli dotyczącej ochrony danych osobowych, z którą należy się zapoznać i podpisać przed przystąpieniem do badania.

Co się stanie z wynikami badania?

Pani/Pana dane, po anonimizacji, zostaną włączone do ogólnej bazy danych uzyskanych od wszystkich uczestników tego badania, na tych danych będą prowadzone analizy statystyczne. Wyniki tych analiz będą prezentowane na konferencjach naukowych o zasięgu międzynarodowym oraz krajowym. Na podstawie tych analiz powstaną również publikacje w czasopismach naukowych. Planowane jest także spotkanie z chętnymi osobami badanymi w celu prezentacji otrzymanych wyników.

Kto finansuje badanie?

Narodowe Centrum Nauki w ramach grantu NCN OPUS (nr. 2019/35/B/HS6/01173)

Szczegółowych informacji o badaniu udziela opiekun naukowy projektu:

Dr hab. Szymon Wichary, prof. UJ

Instytut Psychologii, Wydział Filozoficzny, Uniwersytet Jagiellonski Ul. Ingardena 6, 30 – 060 Kraków, Pokój 4.02.

Tel. 12 6632435; E-mail: szymon.wichary@uj.edu.pl

Lokalizacja:

Badanie odbędzie się w Laboratorium TMS Instytutu Psychologii UJ, znajdującym się na terenie Kliniki Neurologii Szpitala Uniwersyteckiego w Krakowie, przy ul. Botanicznej 3.

Appendix B

A4. Formularz Świadomej Zgody na udział w badaniu z wykorzystaniem Przezczaszkowej Stymulacji Magnetycznej (TMS)

FORMULARZ ŚWIADOMEJ ZGODY

na udział w badaniu eksperymentalnym z wykorzystaniem TMS

w projekcie

„Źródła racjonalności: rola procesów hamowania i ich neuronalnego podłoża w stosowaniu strategii decyzyjnych"

Uczestnik ……..

(Imię i nazwisko)

Data urodzenia:…….

Potwierdzam, że:

- zostałam/-em w zadowalający sposób poinformowana/y przez badacza na temat

wykorzystywanych procedur i towarzyszących im zagrożeń związanych z uczestnictwem w badaniu TMS

- miałam/-em okazję do zadania pytań dotyczących badania TMS i w przypadku niejasnych dla mnie kwestii uzyskałam/-em zadowalające odpowiedzi

- rozważyłam/-em dokładnie swój udział w eksperymencie

- usunęłam/-ąłem z mojego ciała wszystkie metalowe przedmioty (np. kolczyki, pierścionki, naszyjniki, spinki), karty magnetyczne, telefon komórkowy, klucze

- biorę udział w badaniu z własnej woli Rozumiem, że:

- mam prawo do wycofania się z badania w każdym momencie, bez podania przyczyny i ponoszenia jakichkolwiek konsekwencji

- moje dane personalne są chronione zgodnie z polskim prawem. Zgadzam się, że:

- moje zakodowane wyniki badania mogą zostać udostępnione innym badaczom dla celów naukowych/publikacji.

Podpisując ten formularz dobrowolnie, wyrażam zgodę na udział w tym badaniu do chwili zmiany mojej decyzji lub zakończenia badania.

Data i podpis:……. …….

(Czytelny podpis osoby badanej) (Czytelny podpis osoby prowadzącej badanie)

Wyrażam zgodę na kontakt mailowy w sprawie kolejnych badań: Tak / Nie (zakreślić)

Do wypełnienia przez badacza po badaniu

Zgłoszone zdarzenia, skutki uboczne lub odkrycia. TAK NIE (zakreślić)

Jeśli tak proszę opisać:

Data:…… ……

(Czytelny podpis osoby prowadzącej badanie)

A7. Klauzula Informacyjna o Ochronie Przetwarzania Danych Osobowych

INFORMACJA O PRZETWARZANIU DANYCH OSOBOWYCH

Zgodnie z art. 13 Rozporządzenia Parlamentu Europejskiego i Rady (UE) 2016/679 z 27 kwietnia 2016 r. w sprawie ochrony osób fizycznych w związku z przetwarzaniem danych osobowych i w sprawie swobodnego przepływu takich danych oraz uchylenia dyrektywy 95/46/WE (ogólne rozporządzenie o ochronie danych, dalej „Rozporządzenie Ogólne")

Uniwersytet Jagielloński informuje, że:

1. **Administratorem** Pani/Pana danych osobowych jest Uniwersytet Jagielloński, ul Gołębia 24, 31 – 007 Kraków, reprezentowany przez Rektora UJ.
2. **Uniwersytet Jagielloński wyznaczył Inspektora Ochrony Danych**: ul Gołębia 24, 31 – 007 Kraków, pokój 31. Kontakt z Inspektorem możliwy jest przez

   e-mail: iod@uj.edu.pl lub pod nr telefonu 12 663 12 25.

3. Pani/Pana wyniki badań oraz dane osobowe podane w Formularzu Świadomej Zgody na udział w badaniu przetwarzane będą w celach naukowych na podstawie udzielonej zgody na udział w badaniu.
4. Podanie przez Panią/Pana danych osobowych jest dobrowolne, lecz jest warunkiem udziału w badaniu. Konsekwencją niepodania danych osobowych będzie niezakwalifikowanie Pani/Pana osoby do projektu badawczego.
5. Pani/Pana dane osobowe będą/zostaną udostępnione jedynie na wniosek kontroli pod względem wymogów bioetycznych.
6. Pani/Pana dane osobowe nie będą przekazywane do państw trzecich/organizacji międzynarodowych.
7. Pani/Pana dane osobowe będą przechowywane przez okres 5 lat od momentu zakończenia projektu badawczego. Wrażliwe dane osobowe uczestników badania zostaną poddane pseudonimizacji. Każdy z uczestników badania otrzyma kod numeryczny. Dane osobowe zostaną oddzielone od danych naukowych. Klucz (plik przypisujący kod do danych osobowych) będzie przechowywany w zamkniętym pomieszczeniu w Instytucie Psychologii, Wydział Filozoficzny Uniwersytetu Jagiellońskiego, pod nadzorem kierownika projektu dr hab. Szymona Wicharego, prof. UJ, w Krakowie, ul. Ingardena 6.
8. W przypadku konieczności przekazania danych w celach publikacyjnych lub dla innych grup badawczych, dane zostaną poddane anonimizacji – to znaczy opatrzone zostaną

losowo wygenerowanym ciągiem cyfr i liter oraz usunięte zostaną wszelkie fragmenty danych umożliwiające identyfikację osoby, biorącej udział w badaniu.

9. Posiada Pani/Pan prawo do: dostępu do treści swoich danych osobowych oraz ich sprostowania, a także prawo do usunięcia, ograniczenia przetwarzania, przenoszenia danych, wniesienia sprzeciwu wobec przetwarzania – w przypadkach i na warunkach określonych w Rozporządzeniu Ogólnym.
10. Jeżeli przetwarzanie odbywa się na podstawie zgody, posiada Pani/Pan również prawo do cofnięcia zgody w dowolnym momencie bez wpływu na zgodność z prawem przetwarzania, którego dokonano na podstawie zgody przed jej cofnięciem. Wycofanie zgody na przetwarzanie danych osobowych można przesłać e-mailem na adres: mail (szymon.wichary@uj.edu.pl) lub pocztą tradycyjną na adres: Szymon Wichary, Instytut Psychologii UJ, ul. Ingardena 6, 30 – 060 Kraków, lub wycofać osobiście stawiając się pod powyższym adresem, pok. 4.02.

Konsekwencją wycofania zgody na przetwarzanie danych osobowych będzie wycofanie Pani/Pana danych z projektu badawczego.

11. Ma Pani/Pan prawo wniesienia skargi do Prezesa Urzędu Ochrony Danych Osobowych w razie uznania, że przetwarzanie Pani/Pana danych osobowych narusza przepisy RODO.

Potwierdzam, że zapoznałam(-em) się i przyjmuję do wiadomości powyższe informacje.

……..

(miejscowość, data, czytelny podpis)

Appendix C

Zgoda na przetwarzanie danych osobowych

Niniejszym na podstawie art. 9 ust. 2 lit. a RODO **wyrażam zgodę** na przetwarzanie przez Uniwersytet Jagielloński danych osobowych dotyczących mojego zdrowia (danych wrażliwych), uzyskanych w związku z badaniem eksperymentalnym i w wyniku tego badania, w celu realizacji projektu OPUS 18, nr 2019/35/B/HS6/01173 zgodnie z Rozporządzeniem Parlamentu Europejskiego i Rady (UE) 2016/679 z dnia 27 kwietnia 2016 r. (ogólne rozporządzenie o ochronie danych) oraz zgodnie z klauzulą informacyjną dołączoną do mojej zgody.

…….

Miejscowość, data, czytelny podpis

Appendix D

A6. Kwestionariusz Bezpieczestwa przed badaniem z wykorzystaniem Przezczaszkowej Stymulacji Magnetycznej (TMS)

Kwestionariusz bezpieczeństwa w badaniach eksperymentalnych z wykorzystaniem TMS Do wypełnienia przez uczestnika przed badaniem

Udzielone informacje będą traktowane jako poufne

Proszę odpowiedzieć na poniższe pytania:	**Tak**	**Nie**
1. Czy jesteś młodszy/-a niż 18 lat?		
2. Czy jesteś w ciąży lub podejrzewasz że jesteś?		
3. Czy kiedykolwiek doświadczyłeś/-aś urazu głowy, który został zdiagnozowany jako wstrząs lub wiązał się z utratą przytomności?		
4. Czy kiedykolwiek doświadczyłeś udaru mózgu?		
5. Czy kiedykolwiek miałeś operację mózgu?		
6. Czy masz wszczepiony neurostymulator?		
7. Czy masz rozrusznik serca lub cierpisz na choroby serca?		
8. Czy masz wszczepiony implant ślimakowy?		
9. Czy masz wszczepione urządzenie do infuzji leków?		
10. Czy cierpisz na epilepsję albo kiedykolwiek miałeś/-aś drgawki lub napad padaczkowy?		
11. Czy masz problemy ze słuchem lub doświadczasz dzwonienia w uszach?		
12. Czy cierpisz na silne bóle głowy?		
13. Czy przyjmowałeś/-aś jakiekolwiek substancje psychoaktywne w ciągu ostatnich 48 godzin?		
14. Czy tej nocy spałeś krócej niż zazwyczaj? Jeśli tak, proszę sprecyzować jak długo:		
15. Czy posiadasz metalowe elementy/implanty w mózgu, czaszce lub gdziekolwiek w organizmie? Jeśli tak, proszę podać ich lokalizację:		
16. Czy cierpisz na chorobę skóry lub alergię skórną? Jeśli tak, proszę sprecyzować:		

17. Czy ktoś z Twoich bliskich krewnych (rodziców, rodzeństwo, dzieci) choruje na epilepsję lub doświadczył drgawek/napadów padaczkowych? Jeśli tak, proszę sprecyzować:		
18. Czy kiedykolwiek doświadczyłeś/-aś omdlenia lub utraty świadomości? Jeśli tak, proszę podać ile razy i przy jakiej okazji:		
19. Czy kiedykolwiek cierpiałeś/-aś na neurologiczne lub psychiatryczne choroby? Jeśli tak, proszę określić ich rodzaj i okres czasowy:		
20. Czy przyjmowałeś/-aś w ciągu ostatnich dwóch tygodni jakiekolwiek leki, w ramach leczenia lub badań medycznych? Jeśli tak, proszę określić:		
21. W przypadku jakichkolwiek problemów, gdy przechodzą MRI w przeszłości? Jeśli tak, proszę określić:		
22. Czy doświadczyłeś/-aś kiedykolwiek jakichś skutków ubocznych TMS? Jeśli tak, proszę sprecyzować:		
23. Czy spożywałeś alkohol w ciągu ostatnich 12 godzin?		
24. Ile kaw wypiłeś w ciągu ostatnich 12 godzin?		

Ja niżej podpisany/a oświadczam, że przeczytałem i zrozumiałem/am powyższe pytania i biorę pełną odpowiedzialność za podane przez siebie informacje.

Podpis:	Data:

Appendix E

KWESTIONARIUSZ SAMOOCENY STAI
ARKUSZ X-1

Kod pacjenta_____

Data badania _____

Płeć: M K

INSTRUKCJA: niżej podano szereg twierdzeń, przy pomocy których ludzie zwykle opisują samych siebie. Przeczytaj każde z tych twierdzeń, a następnie otocz kółkiem odpowiednią cyfrę na prawo od twierdzenia, aby wskazać, jak ***czujesz się*** właśnie teraz tj. ***w tym momencie***. Nie ma odpowiedzi dobrych i złych. Nie poświęcaj zbyt wiele czasu poszczególnym twierdzeniom. Podawaj odpowiedzi, które jak Ci się wydaje, najlepiej opisują to, co czujesz ***w tej chwili***.

Lp.	TWIERDZENIE	Zdecydowanie nie	Raczej nie	Raczej tak	Zdecydowanie tak
1.	Jestem spokojny	1	2	3	4
2.	Czuję się bezpiecznie	1	2	3	4
3.	Jestem napięty	1	2	3	4
4.	Jestem rozżalony	1	2	3	4
5.	Czuję się swobodnie	1	2	3	4
6.	Jestem przygnębiony	1	2	3	4
7.	Martwię się, czy nie stanie się coś złego	1	2	3	4
8.	Czuję się wypoczęty	1	2	3	4
9.	Odczuwam niepokój	1	2	3	4
10	Jest mi dobrze	1	2	3	4
11	Czuję się pewny siebie	1	2	3	4
12	Jestem zdenerwowany	1	2	3	4
13	Jestem roztrzęsiony	1	2	3	4
14	Jestem „podminowany”	1	2	3	4
15	Jestem odprężony	1	2	3	4
16	Jestem zadowolony	1	2	3	4
17	Jestem zmartwiony	1	2	3	4
18	Czuję się nadmiernie podniecony	1	2	3	4
19	Jestem radosny	1	2	3	4
20	Jest mi przyjemnie	1	2	3	4

KWESTIONARIUSZ SAMOOCENY STAI
ARKUSZ X-2

INSTRUKCJA: niżej podano szereg twierdzeń, przy pomocy których ludzie zwykle opisują samych siebie. Przeczytaj każde z tych twierdzeń, a następnie otocz kółkiem odpowiednią cyfrę na prawo od twierdzenia, aby wskazać, jak się ***zazwyczaj czujesz.*** Nie ma odpowiedzi dobrych i złych. Podawaj odpowiedzi, które jak Ci się wydaje, najlepiej opisują to, jak się ***na ogół*** czujesz.

Lp.	TWIERDZENIE	Prawie nigdy	Czasem	Często	Prawie zawsze
21	Jest mi przyjemnie	1	2	3	4
22	Szybko się męczę	1	2	3	4
23	Chce mi się płakać	1	2	3	4
24	Chciałbym być tak szczęśliwy jak inni	1	2	3	4
25.	Tracę na tym, że nie umiem się dostatecznie szybko decydować	1	2	3	4
26	Czuję się wypoczęty	1	2	3	4
27	Jestem spokojny i opanowany	1	2	3	4
28.	Czuję, że trudności tak się pietrzą, że nie potrafię ich przezwyciężyć	1	2	3	4
29.	Za bardzo martwię się czymś, co w gruncie rzeczy nie jest ważne.	1	2	3	4
30	Jestem szczęśliwy	1	2	3	4
31	Jestem skłonny brać wszystko zbyt poważnie	1	2	3	4
32	Brak mi pewności siebie	1	2	3	4
33	Czuję się bezpiecznie	1	2	3	4
34	Staram się nie zauważać kryzysów i trudności	1	2	3	4
35	Jest mi smutno	1	2	3	4
36	Jestem zadowolony	1	2	3	4
37	Jakaś nieważna myśl chodzi mi po głowie i dręczy mnie	1	2	3	4
38.	Przeżywam rozczarowania tak dotkliwie, że nie mogę przestać o nich myśleć	1	2	3	4
39	Jestem osobą zrównoważoną	1	2	3	4
40.	Staję się napięty lub rozdrażniony, gdy myślę o swoich niedawnych kłopotach	1	2	3	4

Appendix F

SKALA IMPULSYWNOŚCI BARRATTA (BIS – 11)

Kod pacjenta…….....
Data badania …….

Pleć: M K

Instrukcja: Ludzie różnią się tym w jaki sposób myślą i działają w różnych sytuacjach. Ten test ocenia właśnie w jaki sposób Pan/Pani myśli i działa**.** Proszę przeczytać każde podane poniżej zdanie i zaznaczyć właściwą odpowiedź po prawej stronie w kratce (krzyżykiem). Proszę odpowiadać szczerze i nie zastanawiać się zbyt długo nad żadną z odpowiedzi, pierwsza myśl jest zwykle najbardziej trafna.

L.p	Zdania	Rzadko/ Nigdy	Czasami	Często	Prawie zawsze/ zawsze
1.	Dokładnie planuję swoje czynności i zadania.				
2.	Działam bez zastanowienia.				
3.	Jestem beztroski/a.				
4.	Mam gonitwę myśli.				
5.	Planuję wyjazdy z dużym wyprzedzeniem.				
6.	Kontroluję się.				
7.	Łatwo się koncentruję.				
8.	Systematycznie oszczędzam				
9.	Mam trudności, aby usiedzieć spokojnie przez dłuższy czas.				
10.	Dokładnie się zastanawiam				
11.	Dbam o bezpieczeństwo pracy.				
12.	Mówię bez zastanowienia.				
13.	Lubię zastanawiać się nad skomplikowanymi problemami.				

l.p.	Zdania	Rzadko/ Nigdy	Czasami	Często	Prawie zawsze/ zawsze
14.	Zmieniam pracę.				
15.	Działam impulsywnie.				
16.	Szybko nudzę się rozwiązując zadania wymagające myślenia.				
17.	Systematycznie chodzę na badania kontrolne do lekarza lub dentysty.				
18.	Działam pod wpływem chwili.				
19.	Jestem stały/stała w swoich poglądach.				
20.	Zmieniam miejsca zamieszkania.				
21.	Kupuję rzeczy pod wpływem impulsu.				
22.	Kończę to, co zaczynam.				
23.	Chodzę i ruszam się szybko.				
24.	Rozwiązuję problemy na zasadzie prób i błędów.				
25.	Wydaję więcej niż zarabiam.				
26.	Mówię szybko.				
27.	Kiedy się nad czymś zastanawiam rozpraszają mnie inne myśli.				
28.	Bardziej interesuje mnie teraźniejszość niż przyszłość.				
29.	Niecierpliwię się słuchając wykładów, wystąpień lub rozmów.				
30.	Robię plany na przyszłość.				

Appendix G

SKALA POTRZEBY POZNAWCZEGO DOMKNIĘCIA

Kod pacjenta…….....

Data badania …….

Pleć: M K

Instrukcja:
Proszę uważnie przeczytać poniższe twierdzenia. Przy każdym zdaniu należy otoczyć kółkiem odpowiedź, która najlepiej wyraża Pana/Pani opinię. Proszę ustosunkować się do wszystkich twierdzeń. Jeżeli Pan/Pani się pomyli, należy wyraźnie przekreślić pierwszą odpowiedź i zaznaczyć właściwą.

1 – zdecydowanie się nie zgadzam; 2 – nie zgadzam się; 3 – raczej się nie zgadzam; 4 – raczej się zgadzam; 5 – zgadzam się; 6 – całkowicie się zgadzam

1.	Zwykle biorę pod uwagę różne opinie na temat danego zjawiska, nawet wówczas, gdy mam już wyrobiony pogląd.	1	2	3	4	5	6
2.	Unikam niejasnych sytuacji	1	2	3	4	5	6
3.	Myślę, że dobrze uporządkowane życie jest zgodne z moim temperamentem.	1	2	3	4	5	6
4.	Czuję się źle, kiedy nie rozumiem powodów, dla których pewne sytuacje zdarzają się w moim życiu.	1	2	3	4	5	6
5.	Unikam brania udziału w wydarzeniach, nie wiedząc, czego mogę się po nich spodziewać.	1	2	3	4	5	6
6.	Zwykle podejmuję ważne decyzje szybko i pewnie.	1	2	3	4	5	6
7.	Mógłbym opisać siebie jako osobę niezdecydowaną.	1	2	3	4	5	6
8.	Podejmując większość ważnych decyzji, borykam się z mnóstwem sprzeczności.	1	2	3	4	5	6

9.	Przyglądając się większości sytuacji konfliktowych, potrafię zwykle dostrzec racje obu stron.	1	2	3	4	5	6
10.	Unikam przebywania wśród ludzi, którzy są zdolni do nieoczekiwanych działań.	1	2	3	4	5	6
11.	Dopiero ustalenie spójnych reguł umożliwia mi cieszenie się życiem.	1	2	3	4	5	6
12.	Cenię sobie zorganizowany styl życia.	1	2	3	4	5	6
13.	Czuję dyskomfort, gdy czyjeś czyny lub intencje są dla mnie niejasne.	1	2	3	4	5	6
14.	Zwykle dostrzegam wiele możliwych rozwiązań problemu, przed którym stoję.	1	2	3	4	5	6
15.	Unikam sytuacji, których konsekwencji nie da się przewidzieć.	1	2	3	4	5	6

Appendix H

*Contrast Table – Number of cues vs. Stimulation Site * Environment*

Comparison	Estimate	SE	df	t	p
1	-0.9412	0.3296	44.6495	-2.8559	0.0065
2	-0.5964	0.3296	44.6495	-1.8097	0.0771
3	0.0131	0.3296	44.6495	0.0397	0.9685
4	0.0997	0.4198	51.0698	0.2374	0.8133
5	-0.2451	0.4198	51.0698	-0.5838	0.5619

Note. Results are averaged over the levels of Blocks

*Contrast Coefficients - Number of cues vs. Stimulation Site * Environment*

Stimulation site	Environment	Comparison 1	Comparison 2	Comparison 3	Comparison 4	Comparison 5
rIFG	C	|-1	0	0	1	0
Sham		0	-1	0	-1	0
pre-SMA		0	0	-1	0	0
rIFG	NC	1	0	0	0	1
Sham		0	1	0	0	-1
pre-SMA		0	0	1	0	0

Appendix I

*Contrast Table – Decision Time vs. Stimulation Site * Environment*

Comparison	Estimate	SE	df	t	p
1	2.1985	0.8962	44.8831	2.4532	0.0181
2	1.6813	0.8962	44.8831	1.8762	0.0671
3	0.2660	0.8962	44.8831	0.2968	0.7680
4	-0.1360	1.1651	50.4350	-0.1167	0.9076
5	-0.6531	1.1651	50.4350	-0.5606	0.5776

Note. Results are averaged over the levels of Blocks 1 to 6

*Contrast Coefficients - Decision Time vs. Stimulation Site * Environment*

Stimulation Site	Environment	Comparison 1	Comparison 2	Comparison 3	Comparison 4	Comparison 5
rIFG	C	1	0	0	1	0
Sham		0	1	0	-1	0
pre-SMA		0	0	1	0	0
rIFG	NC	-1	0	0	0	1
Sham		0	-1	0	0	-1
pre-SMA		0	0	-1	0	0

Appendix J

*Contrast Table – Relative Strategy Preference vs. Block * Environment*

Comparison	Estimate	SE	df	t	p
1	0.3203	0.0615	78.5172	5.2082	< .001
2	0.2908	0.0615	78.5172	4.7299	< .001
3	0.0654	0.0615	78.5172	1.0629	0.2911
4	-0.2418	0.0615	78.5172	-3.9327	< .001
5	-0.1242	0.0615	78.5172	-2.0195	0.0468
6	0.1471	0.0615	78.5172	2.3915	0.0192

Note. Results are averaged over the levels of Stimulation Sites

*Contrast Coefficients - Relative Strategy Preference vs. Block * Environment*

Environment	Block	Comparison 1	Comparison 2	Comparison 3	Comparison 4	Comparison 5	Comparison 6
C	1	1	0	0	0	0	0
NC		-1	0	0	0	0	0
C	2	0	1	0	0	0	0
NC		0	-1	0	0	0	0
C	3	0	0	1	0	0	0
NC		0	0	-1	0	0	0
C	4	0	0	0	1	0	0
NC		0	0	0	-1	0	0
C	5	0	0	0	0	1	0
NC		0	0	0	0	-1	0
C	6	0	0	0	0	0	1
NC		0	0	0	0	0	-1

Appendix K

*Contrast Table – Relative Strategy Preference (rIFG) vs. Block * Environment*

Comparison	Estimate	SE	df	t	p
1	0.3725	0.0889	216.0883	4.1911	< .001
2	0.3627	0.0889	216.0883	4.0808	< .001
3	-0.0392	0.0889	216.0883	-0.4412	0.6595
4	-0.1373	0.0889	216.0883	-1.5441	0.1240
5	-0.1569	0.0889	216.0883	-1.7647	0.0790
6	0.1863	0.0889	216.0883	2.0955	0.0373

*Contrast Coefficients - Relative Strategy Preference (rIFG) vs. Block * Environment*

Stimulation Site	Environment	Block	Comparison 1	Comparison 2	Comparison 3	Comparison 4	Comparison 5	Comparison 6
rIFG	C	1	1	0	0	0	0	0
rIFG	NC		-1	0	0	0	0	0
rIFG	C	2	0	1	0	0	0	0
rIFG	NC		0	-1	0	0	0	0
rIFG	C	3	0	0	1	0	0	0
rIFG	NC		0	0	-1	0	0	0
rIFG	C	4	0	0	0	1	0	0
rIFG	NC		0	0	0	-1	0	0
rIFG	C	5	0	0	0	0	1	0
rIFG	NC		0	0	0	0	-1	0
rIFG	C	6	0	0	0	0	0	1
rIFG	NC		0	0	0	0	0	-1

Appendix L

*Contrast Table – Relative Strategy Preference (Sham) vs. Block * Environment*

Comparison	Estimate	SE	df	t	p
1	0.4118	0.0889	216.0883	4.6322	< .001
2	0.2843	0.0889	216.0883	3.1985	0.0016
3	0.0686	0.0889	216.0883	0.7720	0.4409
4	-0.3922	0.0889	216.0883	-4.4117	< .001
5	-0.0980	0.0889	216.0883	-1.1029	0.2713
6	0.0882	0.0889	216.0883	0.9926	0.3220

*Contrast Coefficients - Relative Strategy Preference (Sham) vs. Block * Environment*

Stimulation Site	Environment	Block	Comparison 1	Comparison 2	Comparison 3	Comparison 4	Comparison 5	Comparison 6
Sham	C	1	1	0	0	0	0	0
Sham	NC		-1	0	0	0	0	0
Sham	C	2	0	1	0	0	0	0
Sham	NC		0	-1	0	0	0	0
Sham	C	3	0	0	1	0	0	0
Sham	NC		0	0	-1	0	0	0
Sham	C	4	0	0	0	1	0	0
Sham	NC		0	0	0	-1	0	0
Sham	C	5	0	0	0	0	1	0
Sham	NC		0	0	0	0	-1	0
Sham	C	6	0	0	0	0	0	1
Sham	NC		0	0	0	0	0	-1

Appendix M

*Contrast Table – Relative Strategy Preference (pre-SMA) vs. Block * Environment*

Comparison	Estimate	SE	df	t	p
1	0.1765	0.0889	216.0883	1.9852	0.0484
2	0.2255	0.0889	216.0883	2.5367	0.0119
3	0.1667	0.0889	216.0883	1.8750	0.0621
4	-0.1961	0.0889	216.0883	-2.2058	0.0284
5	-0.1176	0.0889	216.0883	-1.3235	0.1871
6	0.1667	0.0889	216.0883	1.8750	0.0621

*Contrast Coefficients - Relative Strategy Preference (pre-SMA) vs. Block * Environment*

Stimulation Site	Environment	Block	Comparison 1	Comparison 2	Comparison 3	Comparison 4	Comparison 5	Comparison 6
pre-SMA	C	1	1	0	0	0	0	0
pre-SMA	NC		-1	0	0	0	0	0
pre-SMA	C	2	0	1	0	0	0	0
pre-SMA	NC		0	-1	0	0	0	0
pre-SMA	C	3	0	0	1	0	0	0
pre-SMA	NC		0	0	-1	0	0	0
pre-SMA	C	4	0	0	0	1	0	0
pre-SMA	NC		0	0	0	-1	0	0
pre-SMA	C	5	0	0	0	0	1	0
pre-SMA	NC		0	`0	0	0	-1	0
pre-SMA	C	6	0	0	0	0	0	1
pre-SMA	NC		0	0	0	0	0	-1