COMENIUS UNIVERSITY IN BRATISLAVA
FACULTY OF MATHEMATICS, PHYSICS AND INFORMATICS

THE ROLE OF THE LEFT INFERIOR FRONTAL CORTEX IN SEMANTIC RETRIEVAL: A tDCS STUDY

Diploma thesis

2019

Bc. Ondrej Hadidom

COMENIUS UNIVERSITY IN BRATISLAVA
FACULTY OF MATHEMATICS, PHYSICS AND INFORMATICS

THE ROLE OF THE LEFT INFERIOR FRONTAL CORTEX IN SEMANTIC RETRIEVAL: A tDCS STUDY

Diploma thesis

Study program: Cognitive Science

Field of study: 2503, Cognitive Science

Institute of supervision: Centre of Experimental Medicine Slovak Academy of Science, Institute of normal and pathological physiology

Supervisor: Mgr. Martin Marko, PhD.

2019

Bc. Ondrej Hadidom

Univerzita Komenského v Bratislave
Fakulta matematiky, fyziky a informatiky

ZADANIE ZÁVEREČNEJ PRÁCE

Meno a priezvisko študenta: Bc. Ondrej Hadidom
Študijný program: Kognitívna veda (Jednoodborové štúdium, magisterský II. st., denná forma)
Študijný odbor: Kognitívna veda
Typ záverečnej práce: Diplomová práca
Jazyk záverečnej práce: anglický
Sekundárny jazyk: slovenský

Názov: The role of left inferior frontal cortex in semantic retrieval: a tDCS study
Úloha ľavej inferiórnej frontálnej kôry pri sémantickom vybavovaní: tDCS štúdia

Anotácia: Množstvo dôkazov indikuje, že ľavá inferiórna frontálna kôra (LIFC) je významným neurálnym substrátom pre sémantické kognitívne procesy. Súčasné štúdie naznačujú, že stimulácia pomocou tDCS v oblasti LIFC zlepšuje kognitívny výkon u pacientov, a to pravdepodobne facilitáciou exekutívnych funkcií spojených so sémantickou pamäťou. Presný neurokognitívny mechanizmus tohto účinku však zostáva neznámy.

Cieľ: Bližšie preskúmajte rolu LIFC pri sémantickom vybavovaní: Zdraví pacienti budú testovaní v rámci vybavovania pri automatických asociáciách a kontrolovaných disociáciách, počas toho ako ich LIFC oblasť bude stimulovaná prostredníctvom tDCS. Precíznou analýzou latencie pri vybavovaní v rôznych experimentálnych podmienkach, zhodnoťte úlohu LIFC v sémantickom spracovávaní.

Literatúra: Joyal, M., & Fecteau, S. (2016). Transcranial Direct Current Stimulation Effects on Semantic Processing in Healthy Individuals. *Brain Stimulation*, *9*(5), 682–691.
Pisoni, A., Mattavelli, G., Papagno, C., Rosanova, M., Casali, A. G., & Romero Lauro, L. J. (2018). Cognitive Enhancement Induced by Anodal tDCS Drives Circuit-Specific Cortical Plasticity. *Cerebral Cortex*, *28*(4), 1132–1140.

Vedúci: Mgr. Martin Marko, PhD.
Katedra: FMFI.KAI - Department of Applied Informatics
Vedúci Katedry: prof. Ing. Igor Farkaš, Dr.

Dátum zadania: 25.02.2019

Dátum schválenia: 25.02.2019

prof. Ing. Igor Farkaš, Dr.
garant študijného programu

....

študent vedúci práce

Comenius University in Bratislava
Faculty of Mathematics, Physics and Informatics

79089774

THESIS ASSIGNMENT

Name and Surname:	Ondrej Hadidom
Study programme:	Cognitive Science (Single degree study, master II. deg., full time form)
Field of Study:	Cognitive Science
Type of Thesis:	Diploma Thesis
Language of Thesis:	english
Secondary language:	slovak

Name: The role of left inferior frontal cortex in semantic retrieval: a tDCS study
Úloha ľavej inferiórnej frontálnej kôry pri sémantickom vybavovaní: tDCS štúdia

Anotation: Evidence points to left inferior frontal cortex (LIFC) as a crucial neural substrate for semantic cognition. Recent studies indicate that tDCS over LIFC can improve such a cognitive performance in patients, presumably by enhancing executive functions bonded to semantic memory. However, the precise neurocognitive mechanisms of these effects remain largely unknown.

Aim: Investigate the role of LIFC in semantic retrieval: healthy participants will be assessed for automatic–associative and controlled–dissociative retrieval measures while receiving anodal/sham tDCS over LIFC. Using a fine-grained analysis of retrieval latencies from various experimental conditions, evaluate the respective role of LIFC in semantic processing.

Literature:
Joyal, M., & Fecteau, S. (2016). Transcranial Direct Current Stimulation Effects on Semantic Processing in Healthy Individuals. *Brain Stimulation*, *9*(5), 682–691.
Pisoni, A., Mattavelli, G., Papagno, C., Rosanova, M., Casali, A. G., & Romero Lauro, L. J. (2018). Cognitive Enhancement Induced by Anodal tDCS Drives Circuit-Specific Cortical Plasticity. *Cerebral Cortex*, *28*(4), 1132–1140.

Supervisor: Mgr. Martin Marko, PhD.
Department: FMFI.KAI - Department of Applied Informatics
Head of department: prof. Ing. Igor Farkaš, Dr.

Assigned: 25.02.2019

Approved: 25.02.2019 prof. Ing. Igor Farkaš, Dr.
garant študijného programu

....

študent vedúci práce

Declaration

I hereby declare that I elaborated this diploma thesis independently using the cited literature.

Acknowledgment

I would like to thank to my supervisor Mgr. Martin Marko, PhD. for his guidance, methodological supervision and valuable advices, which help me through the whole process of writing this diploma thesis.

Abstrakt

HADIDOM, Ondrej: Úloha ľavého laterálneho infriórneho frontálneho kortexu pri sémantickom vybavovaní: tDCS projekt. [Diplomová práca]. – Univerzita Komenského v Bratislave. Fakulta matematiky, fyziky a informatiky; Katedra Aplikovanej informatiky. – Školiteľ: Mgr. Martin Marko, PhD. Stupeň odbornej kvalifikácie: Magister. Bratislava: FMFI UK, 2019. 64s.

Naše všeobecné znalosti o okolnom svete sú uložené v sématickej pamäti a reprezentované vo forme pojmov. Zapojenie rozličných mechanizmov sémantického vybavovania je potrebné, aby sme boli schopní s pojmami efektívne narábať. Okolitý kontext nám poskytuje podnety, ktoré automaticky a bez zámerného úsilia vedú k vyvolaniu sémantických reprezentácií, avšak ak tieto podnety absentujú alebo sú nedostatočné, musíme zapojiť kognitívne zdroje umožňujúce kontrolované sémantické vybavovanie spomienok. Kognitívna kontrola zahŕňa v sebe aspekty, ako inhibícia prepotentných odpovedí a kognitívna flexibilita umožňujúca presúvať pozornosť medzi atribútmi úlohy. Ľavý laterálny inferiórny frontálny kortex (LIFK) je predpokladanou neurálnou štruktúrou zodpovednou za produkčné aspekty jazykového spracovávania a kontrolovaného sémantického vybavovania. V rámci tohto projektu sme sa zamerali na transkraniálnu stimuláciu jednosmerným prúdom (tSJP). Predpokladá sa, že neurostimulácia ľavého LIFK prostredníctvom slabého jednosmerného prúdu vedie k zlepšenému výkonu v lexikálno-sémantickej úlohe. Avšak, efekty tSJP na LIFK v rámci špecifických pred-vybavovacích a po-vybavovacích mechanizmov zostávajú neobjasnené. V tomto projekte sme aplikovali anodálnu tSJP na LIFK v úlohe umožňúcej rozlišovať špecifické aspekty sémantického vybavovania (kategorická verbálna fluencia, produkcia associácií, produkcia disociácií, produkcia slov bez počiatočného podnetu). Participanti (N=27) boli testovaní v rámci vnútrosubjektového dizajnu pozostávajúceho z troch po sebe nasledujúcich stretnutí oddelených minimálne piatimi dňami. Analyzované dáta naznačujú, že tSJP aplikovaná na oblasť LIFK, signifikantne zlepšuje kontrolované sémantické spracovávanie v podmienkach merajúcich kategorickú verbálnu fluenciu a produkciu dissociácií. Výsledky nás vedú k záveru, že použitá neurostimulácia viedla k posilneniu kontrolovanej inhibície prepotentných automatických odpovedí.

Kľúčové slová: kontrolované sémantické vybavovanie, transkraniálna stimulácia jednosmerným elecktrickým prúdom, ľavý laterálny inferiórny frontálny kortex

Abstract

HADIDOM, Ondrej: The role of the left inferior frontal cortex frontal cortex in semantic retrieval: a tDCS study. [Diploma Thesis]. – Comenius University in Bratislava. Faculty of Mathematics, Physics and Informatics; Department of Applied Informatics. – Supervisor: Mgr. Martin Marko, PhD. Qualification Degree: Master. Bratislava: FMPH CU, 2019. 64p.

Our general knowledge about the world is stored in semantic memory in form of conceptual representations. In order to efficiently use these concepts, employment of various semantic retrieval mechanisms is required. Context can provide cues automatically and effortlessly eliciting semantic memories, however in case of their absence or insufficiency we need to devote our cognitive resources to controlled semantic retrieval. Cognitive control encompasses aspect as inhibition of prepotent habitual responses and switching providing us with cognitive flexibility in task-dependent context. Left lateral inferior frontal cortex (LIFC) has been proposed as vital neural substrate responsible for language production processing and controlled semantic retrieval. Transcranially delivered neurostimulation of left LIFC via low-intensity direct current (tDCS) has been also suggested to enhance performance in lexical-semantic task. However, effect of tDCS over LIFC on specific pre-retrieval and post-retrieval semantic processing remains to be undescribed. In this project we applied anodal tDCS over LIFC and administered tasks allowing us to distinguish between specific aspects of semantic retrieval (categoric verbal fluency, associative words production, dissociative words production, production of words without prime). We tested participant (N=27) in within subject design consisting of three consecutive sessions devided by least 5 days. Analysed data suggestsed that tDCS applied over left LIFC may improve controlled semantic processing, as assessed by categoric verbal fluency and dissociative word production measures. According to our results we conclude that used neurostimulation resulted in boosted controlled inhibition of prepotent automatic responses.

Key words: controlled semantic retrieval, transcranial direct current stimulation, left lateral inferior frontal cortex

Content

Introduction

Lexical-semantic processing is fundamental for everyday functioning. Human semantic system is implemented by a number of cortical regions and networks that spread from posterior temporal-parietal converging zones to high-order multimodal prefrontal association areas. These brain regions are dynamically and flexibly connected to ensure a highly integrative process. Importantly, semantic processing is a hallmark of human cognition and behavior. It is central to language and capacity to access acquired knowledge in reasoning, planning, and problem solving (Binder et al., 2009).

Growing body of evidences indicates that left lateral inferior frontal cortex (LIFC) is pivotal for semantic cognition (Whitney et al., 2011; Joyal et al., 2016; Ralph et al., 2017). According to the influential meta-analytical review by Binder and colleagues (2009), robust neuroimaging evidence demonstrates that LIFC is crucially implicated in semantic, syntactic, and phonological processing. This functionality seems to follow an anterior-ventral to posterior-dorsal neuroanatomical gradient (Hagoort, 2005), suggesting a fine-grained and multifaceted functional specialization within LIFC. Interestingly, the BOLD (blood oxygen level-dependent) activity in LIFC elevates as a function of increased semantic processing demands, indicating that this region may specifically support complex semantic computations. Although a number of influential neurocognitive models has been proposed, the current understanding of the functional role of LIFC in semantic cognition remains unknown and thus requires further investigation.

In this project, we addressed this issue using transcranial direct current stimulation approach (tDCS). TDCS is a non-invasive brain stimulation (NIBS) technique utilizing constant weak currents delivered to targeted brain regions via electrodes attached on the head. A portion of the exogenously induced current passes the brain tissue and modulates its physiological and functional properties as a result. TDCS is the only NIBS delivering constant stimulation and therefore it is unique in comparison to other NIBS, which are stimulating with pulses or alternating currents (Reti, 2015). This approach can bring important evidence about the underlying neural substrates and computations supporting semantic cognition. Such knowledge can provide the necessary framework for enhancing cognitive semantic processing in healthy individuals, as well as for the development of novel non-pharmacological interventions for patients. Importantly, the current neurocognitive model of semantic cognition implies, that access to semantic knowledge emerges from an interplay of multiple distinct processes, including both automatic (i.e., "stimulus-driven") and the controlled (i.e., "top-down") cognition (Badre & Wagner, 2007). Following the current trends, our project utilizes an innovative methodology enabling quantitative description of multiple distinct retrieval measures (i.e., automatic – associative and controlled – dissociative) (Marko et al., 2018a). This subdivision can shed light into the fine-grained cognitive architecture of semantic retrieval.

Empirical evaluation of anodal tDCS influence on LIFC, in context of task-specific semantic retrieval, may contribute to better understanding of the mechanism of (controlled) semantic retrieval and the nature of neurocognitive processing implemented by LIFC. Such evidence could not only extend the current understanding of semantic cognition, but also provide the necessary framework for the development of effective treatment of clinical conditions associated with impaired semantic functioning.

1 Semantic memory

Human experiences acquired through life are structured and stored in large distributed memory networks. Our memory is not a unitary system, however. Distinct memory systems are responsible for remembering, which is determined as a function of time (i.e., short-term versus long-term memory systems) and form of acquisition and access (i.e., explicit or implicit memory systems), which is associated with distinct neuroanatomical and functional properties. In this section, we will introduce the concept of semantic memory, which is a form of long-term, declarative (explicit) memory system that is responsible for the encoding, retention, and retrieval of stored concepts, facts and regularities derived from the experience (Sternberg & Sternberg, 2011)

Memory consists of two fundamental types: declarative (explicit) memory and nondeclarative (implicit) memory. Subsequent division of declarative memory also comprises of two types: semantic memory and episodic memory. Conceptual distinction between them belongs to Endel Tulving (1972), who genuinely referred to difference between remembering and knowing. According to Tulving remembering is specifically connected with time and place in the personal past, whereas knowing is factual based. Subjectively experienced episodes and events are stored in episodic memory, which is employed in recalling memories associated with specific time or context. In contrast to episodic memory, semantic memory stores general world knowledge. We can make explicit declaration about content stored in it, but compared to episodic memories linked to events (i.e., how and where did my sister learn to swim), content of semantic memory consists of broader information and facts about world (i.e., what does concept of „swimming“ mean). Comprehension is vital component of sematic system, whereas in case of episodic memory mere sensation of a stimulus can serve as a source of information. Semantic memory storage encompasses conceptual representations and it is "the memory necessary for the use of language. It is a mental thesaurus, organized knowledge a person possesses about words and other verbal symbols, their meaning and referents, about relations among them, and about rules, formulas, and algorithms for the manipulation of the symbols, concepts, and relations" (Tulving, 1972).

From the perspective of time-span, for which content remain stored, semantic memories can last a lifetime. Work of Smith (2005) shed light on acquiring of new conceptual knowledge in young children (2 y.o.). If child was given a novel object with possibility of horizontal extension, it will likely consider it as member of different category than another object with possibility of vertical extension. From this developmental perspective sensory-motor information has important influence on categorization process and affects conceptual representation. Squire & Zola (1998) in review on interdependency of semantic and episodic memory concludes that semantic memories accumulated throughout the life in semantic memory stems from episodic memory. This suggestion is based on the argument that everyday experiences share common attributes and existing regularities between first genuine experience and following one enables us to derive concepts as representations of set of regularities. Accumulation of experiences followed by abstraction of regularities leads to creation of factual knowledge, which is comprehended and stored in long-term memory. However, neuropsychological evidences from amnestic patients (O'Kane et al., 2004; Bayley & Squire, 2005) reveal greater independency of semantic and episodic memory. Patients in those studies weren´t able to acquire new episodic memories, but ability to acquire new semantic knowledge remained contact. Even when brain injury provoking amnesia happened in young age (9 y.o.) and structures for episodic memory were impaired, patients were still able to learn, understand and memorize new conceptual knowledge (Bindschaedler et al., 2011). This perspective proposes acquiring of semantic memories as independent from episodic memory.

Intersection of approaches to interdependency of semantic and episodic memory can be conceptually explained as follows: through development of children, direct sensory-motor representation is gradually replaced by semantic representations relying on abstract information. Increasing relying on abstract information results in advanced ways of acquiring semantic representations such as through verbally described definitions or analogies. Manipulation of abstract concepts allows categorization and generalization, which are inevitable for the ability to structure the knowledge about surrounding environment. Once conceptual knowledge is memorized (e.g. "Egg") and new experience with object from category is encountered, previously stored semantic knowledge can be used to map on even non-evident properties (e.g. soft inside). This conceptual knowledge about world is advantageous since it enables adaptive and efficient cognitive flexibility. Also, formation of semantic structures (i.e., routines, scripts, and predictions) alleviate cognitive demands associated with cognitive processing and decision making, and thus ensure optimal cognitive economy (Wixted & Thompson-Schill, 2018).

1.1 Structure of semantic memory

A number of models describing the acquisition and organization of concept structures has been proposed. The earlier philosophical accounts viewed concepts as consisting from simpler parts, each considered to be concept per se. For example, concept „bird“ can be formed from simpler definitional parts, such as „wings“ + „feather“ + „flying“. Accordingly, all defining features must be satisifed in order to consider something as „a bird“. Since object categorization requires a number of rules to be met, this approach is sometimes also referred to as rule-based categorization. Limitation of this approach lies in fact that not every concept can be precisely defined by an exhaustive and invariant set of features (e.g., what defines a game?; Wittgenstein, 1968).

Second perspective attempts to understand concepts in terms of prototypes positing them as structured and categorized on the basis of similarity, rather than on a set of rigid rules. In cognitive psychology, such approach has been referred to as a prototype theory (Rosch, 2002). From the viewpoint of prototype theory, concepts are probabilistic and without precise definitional structure. Features belonging to the concept are weighted based on the frequency of their co-occurrence: highly frequent co-occurrence of a features makes the feature more prototypical (i.e., strengthens the weight between the feature and a concept). Since prototypes are represented as weighted averages across their most typical features, even unknown phenomena and object may be considered an instance of a prototypical concept.

Third viewpoint challenges the assumptions made about concepts as based on weighted maps of typical features. Exemplar model, proposed by Medin and Schaffer (1978), posits that decision whether an object belongs to a category is based on comparison with previously stored experiences.

It is still matter of discussion, which of mentioned approaches is correct and there are also attempts to build a full theory of categorization combining prototypical and defining features (Poitrenaud et al., 2005). According to this theory each category encompasses prototypical features on periphery and a core consisting of defining features. Empirical examples acquired through the life lead to better structuring and finer-grained categorization. Sets of regularities between examples may further be stored as abstraction (Wixted & Thompson-Schill, 2018).

1.2 Storing of information in semantic memory

While considering semantic memory, it is important to understand the way how semantic representations are stored. There are two hypotheses aiming to explain how semantic knowledge is represented in semantic memory. The first one is called Sensory-motor hypothesis and proposes that certain semantic features are stored in modality specific brain regions (Farah & McClelland, 1991). According to this hypothesis distinction between categories and concepts is based on differences in the underlying patterns of sensory-motor activations. For instance, we can demonstrate this distinction in categories like „tools“ and „plants“. Since „tools“ have more instrumental features (i.e., „What to do with it?“) and “plants” have more descriptive features (i.e., „How does it look like?“), these two categories/concepts involve activation of distinct sensory-motor modalities, i.e., motor and visual, respectively. The notion of category-specific organization of knowledge is supported by evidence from neurological patients, indicating that brain lesions in areas processing specific modalities of stimuli are associated with category-specific semantic deficits. For example, patients may encounter troubles in retrieving objects from a certain category (i.e. “tools”), whereas retrieving in other categories may remains intact (i.e. „animals“ or „fruits“) (Garrard et al., 2001).

An alternative explanation of the category-specific deficits has been posited by so called „distributed models“ of semantic cognition emphasizing that semantic representations are widely distributed throughout the cortex (Gonnerman et al., 1997). Distributed models of semantics are suggesting that categories including multiple shared features are less sensitive to be disrupted by brain damage, whereas categories sharing fewer common features are more affected by brain damage. The level of category specificity implies the degree of vulnerability to impairment. For example, „animals“ can be defined by multiple features. Therefore, if a traumatic injury impairs the underlying semantic structure (i.e. concept „dog“ having a feature „tail“), we might still be able to recognize a „dog“ based on compensatory features (i.e. „head“, „four legs“, „fur“), enabling us to categorize „a dog“ as „an animal“. Accordingly, categories with fewer shared features are more substantially affected by disruptions. From the perspective of distributed models, spreading brain damage will lead to increasingly difficult compensating for missing knowledge (Hart & Kraut, 2007).

1.3 Process of retrieval from semantic memory

Once information is stored in semantic memory, it is also important to understand how it is retrieved. To be behaviorally efficient, it is important to retrieve relevant knowledge for the given context or situational demands. Otherwise, the behavior would be disorganized and maladaptive. Connectionist parallel distributed processing (PDP) models knowledge representation as connections between nodes, but not by individual nodes (Feldman & Shastri in Nadel, 2003). If one node is activated, the adjacent nodes receive activation that spreads through the network to form a specific activation pattern. The pattern of activation in a network represents stored knowledge. With this regard, we need to focus on retrieving of semantic information from interconnected network. A number of studies has suggested that semantic retrieval emerges from interaction of two conceptually distinct systems for semantic representation and semantic control (Whitney et al., 2011). These systems have different neural underpinnings and provide different functions. Taken those differences into account, two complementary categories of processes can be described: automatic and controlled (Badre & Wagner, 2007). Automatic retrieval processes allow quick and efficient activation of knowledge (i.e., word associations), whereas controlled processes are employed when automatically retrieved information is inadequate for current context or task demands (e.g., task demanding on uncommon solution, divergent thinking or conceptual framing).

Content of semantic memory may be recalled automatically. Automatic processes in general are mostly performed without conscious awareness with little recruitment of attentional resources. They are effortless, do not require intention and multiple of them can occur parallelly (Posner & Snyder, 2004). Node inside a network called prime stimulates activation of other nodes connected to it. Result of prime activation is referred to as priming effect, which leads to an enhanced identification of a word or object „by the presentation of a related stimulus or by a prior processing episode involving that word or object“ (Masson, 2001). Priming effect evokes automatic spreading activation resulting in facilitated identification of semantically related word. Automatic activation of semantic knowledge elicits strongly associated prepotent habitual responses, which are entering consciousness automatically without any effort (Miyake et al, 2000).

Considering engagement of cognitive control in process of semantic retrieval, two crucial aspects have to be highlighted. From perspective of cognitive control engagement, the effortless way to retrieve semantic information involves *automatic retrieval*. For retrieval in this way, cues triggering the activation of associated information are necessary. Because the presence of sufficiently associative cues is needed, this way if information retrieval is also called "stimulus-driven" (Badre & Wagner, 2002).

In comparison to automatic processes, *controlled processes* require conscious control. They are effortful and demanding on limited cognitive resources. Controlled processes are performed sequentially, and their duration is longer, than in automatic processes (Sternberg & Sternberg, 2011). „Cognitive control refers to the ability to pursue goal-directed behaviour, in the face of otherwise more habitual or immediately compelling behaviours" (Cohen in Egner, 2017). We recruit cognitive control in planning, problem solving, and also language processing. Not every occasion enables automatic retrieval of information and cues present in the context are not always sufficient to eable an automatic stimulus-driven retrieval. Cues in such context may be weakly associated with the relevant information, non-specific or completely absent. In situation, where redundant amount of information is retrieved, selection of appropriate concepts from competitive alternatives is desired. If target in memory isn´t automatically retrieved by cues, cognitive control is vital for goal-directed activation of relevant representations stored in semantic memory. Under the domain of cognitive control, there are two main executive functions that may participate during retrieval: inhibition of prepotent automatic response and switching dynamically between associations and dissociations. The engagement of these executive aspects are dependent on the task semantic memory functioning (Dudukovic & Kuhl in Egner, 2017). In contrast to automatic retrieval, this type of recalling is called *controlled retrieval*. Further division of controlled retrieval into functional subsections includes: specification of relevant cues, elaboration, maintenance, and retrieval plans.

Before content from semantic memory is retrieved, pre-retrieval mechanism of controlled retrieval is employed. It´s recruitment is required, when cues are not sufficient to evoke automatic activation of the relevant semantic representations. Controlled retrieval mechanism elicits activation of goal-relevant semantic representations in top-down manner. *Pre-retrieval* mechanism is involved in effortful strategic search for relevant content in semantic memory. Mechanism of *post-retrieval selection* works with the already retrieved tokens or lexical representations consciously available for further selection or inhibition. Mechanism of selection resolves the competition among multiple, simultaneously active representations, which are in state of proactive interference. To the state of proactive interference may enter representations retrieved in automatically or controlled manners (Badre et al., 2005; Badre & Wagner, 2007).

Cognitive control enables us to strategically utilize our semantic knowledge in order to act flexibly. Both pre-retrieval and post-retrieval mechanisms further serves as top-down signals guiding semantic memory retrieval or shaping the semantic space, from which the information is retrieved. Mechanisms of controlled retrieval and post-retrieval selection appear crucial for mnemonic control in various task domains. Controlled retrieval functions are usually assessed using experimental designs involving various conditions and experimental manipulation of judgement specificity, congruency or associative strength. Experimental approach to controlled retrieval often involves tasks demanding on lexical-semantic representations and their associative or dissociative relationships (Badre & Wagner, 2007).

2 Brain areas responsible for semantic processing

The phylogenetic development of semantic functions involved several crucial evolutionary adaptations leading to profound modification of the brain's architecture. From present perspective is observable dominance of cerebrum. Growing cortex inside limited cranial volume has led to its wrinkled surface ensuring its maximal contained amount. Such changes in humans resulted in very idiosyncratic capacities pertaining to language and semantics that cannot be observed in the same extent in any other primate. Size and density of cortex is suggested to be cause of these differences. Mainly, human frontal lobe, one of four main neuroanatomically distinct brain lobes, is proportionally bigger and denser to whole body, than in any other species (Aboitz, 2017). Frontal lobe generally enables us very complex thinking in process of problem solving. (Duverne & Koechlin in Egner, 2017).

Heading to forward-most part of the frontal lobe, we are approaching prefrontal cortex (PFC). PFC is the cortical area responsible for executive functions, such as planning, conscious judgement, self-reflection, and what is scope of our work crucial, cognitive control of retrieval from memory. This proportionally large neural substrate is generally responsible for action outcomes and selecting actions in response to stimuli. PFC provides us with ability to "organize thoughts and actions in relation to current mental states, which are in turn the product of cognitive control processes" (Duverne & Koechlin in Egner, 2017). Due to the ability to anticipate, plan, and control our behavior, we can overcome a number of evolutionary and socially important limitations, which another sub-human species face. In the context of adaptive behavior, cognitive control in PFC has likely evolved to overcome constraints of reinforcement learning encompassing basal ganglia and premotor cortex. Adaptation to new situations in reinforcement learning gradually leads to fade away of previous successful behavioral strategies. Cognitive control mechanism goes beyond this limitation (Koechlin, 2014). The PFC in sub-human mammalian brain and in rodents consists mainly from paralimbic regions and anterior cingulate cortex (Uylings et al., 2003), but the relative volume of PFC does not differ from humans (Semendeferi et al., 2001). In primates, the development of PFC continued in development of lateral regions (Fuster, 1989 in Robbins, 1990). The emergence of left-right asymmetry is typical only for humans and it resulted in the development of larger associative regions, which are responsible for inferential, hierarchical semantic control and language production (Koechlin, 2014). PFC activity has been associated with cognitively controlled access and retrieval from semantic memory structures. Increased activity in left inferior cortical subsections of the PFC was observed in tasks involving semantic generation and semantic judgement. Importantly, PFC has been repeatedly suggested as the most important region supporting the access to goal-relevant knowledge and semantic inferences (Wagner et. al., 2001).

2.1 Semantic system and brain corelates of semantic cognition

Sometimes, knowledge important for our goals and task-fulfillment at hand, comes to our mind automatically, without any effort. Such an automatic process of knowledge retrieval is evoked simply by the presence of stimuli in our environment. However, in many situations relevant knowledge from acquired experiences do not readily comes to our minds (Badre & Wagner, 2007). In these instances, the search for information requires additional support by executive attention and cognitive control mechanisms. This effortful mediation is referred to as controlled semantic retrieval. Considering semantic relationships between stored representations we have devote our attention also to language.

2.1.1 Broca´s area and lateral inferior frontal cortex

Neural corelate responsible for speech production is Broca´s area (BA). Pierre Paul Broca originally described this specific area together with its functions in 1861, when he reported case of aphasic patient suffering from lesion in this area. This patient became famous as „tan“ patient, since his lesion on BA has led to speech impairment constraining him to say only „tan“ word, but understanding of speech remained normal (Aboitiz, 2017). In case of patient suffering from this kind of aphasia without any other comorbidity, ability to think in words, write them down and understand their meaning remains intact. „The motor speech area of Broca is located in the inferior frontal gyrus between the anterior and ascending rami and the ascending and posterior rami of the lateral fissure (Brodmann´s areas 44 and 45)" (Splitberger, 2018). BA, localized in PFC, consists of three subdivisions. From left side-perspective of the brain, the most upper part of PFC is superior frontal gyrus bordering via superior frontal sulcus with the second subdivision called middle frontal gyrus. Third part, divided by inferior frontal sulcus, is called inferior frontal gyrus (IFG). To cortical part of IFG, from now on, we will refer as the lateral inferior frontal cortex (LIFC). From cytoarchitectonic perspective, LIFC consists of orbital, triangular and opercular portions referring to Brodmann´s areas 47, 45, 44 (see Fig. 1). LIFC is a subpart of PFC primarily associated with cognitive ability of controlled semantic retrieval (Carter, 2019). Current state of knowledge in area of semantic cognition posits LIFC as critical for control of semantic retrieval (Badre & Wagner, 2005; Badre & Wagner, 2007).

2.1.2 Representation and retrieval of semantic knowledge

Semantic knowledge does not serve merely to producing and understanding of language, but it is also used in a number of non-verbal behaviours. Semantic knowledge converts unorganized and meaningless sensory inputs into meaningful and comprehensible structures enabling recognition of objects, as well as derivation of inferences about these objects and events present in environment. Perception, attention, but also behavioral acts, are therefore supported by semantic knowledge (Hart & Kraut, 2007).

Semantic cognition has been suggested to consists of two interacting neural systems. This two-system perspective has been referred to as *controlled semantic cognition framework*. (Ralph et. al., 2017). The first principal system is devoted to semantic representations. This system is responsible for the encoding of conceptual knowledge mediated by formation of complex relations among motor, linguistic, sensory and affective sources extensively distributed in the cortex. Similarly, as introduced by Patterson and colleagues (2007) in their „hub-and-spoke“ theory, conceptual knowledge is acquired via learning from statistical structures built on the basis of our multimodal experiences. First important aspect of this theory lies in the assumption, that multimodal verbal and non-verbal experiences acquired during lifespan are vital for concept creation. Modality specific cortices, spread across the brain, are responsible for encoding of conceptual information. It has been proposed that semantic representations are stored in category-specific way, because certain specific categories as "animals" have higher importance for survival. Such natural kind of category was likely to be selected, because it aided a successful identification of potential risks in form of predators (Caramazza, 1998). Therefore, category-specific way of knowledge representation might be beneficial for survival. The „hub-and-spoke“ model also posits existence of transmodal hub positioned bilaterally in anterior temporal lobes (ATLs). This hub enables cross-modal interactions for modality specific sources (Patterson et. al, 2007). Studies on semantic dementia (SD) support the suggestion that ATL represents a cross-modal region, since impairments across all modalities and types of concepts in patients diagnosed with SD have been documented (Bozeat et al., 2000).

This account was challenged because of two reasons: (1) experiences relevant to the concept are acquired in different time point for each modality, (2) conceptual structure is not transparent in in linguistic or senso-motoric structure, but rather complex and nonlinear. Neural network model, from McClelland & Rogers (2003) operating with intermediating hub devoted to all concepts and modalities, can however solve these problems.

The second system represents semantic control. This system modulates the activation pattern within representational system to produce inferences and behaviours that are suitable for contextual and temporal aspects of task. Fulfilling of some tasks requires attention devoted to accentuating of subtle, hidden meanings and features, or to suppressing of prepotent habitual responses respectively. Furthermore, meaning of the same concept, either verbal or non-verbal, may vary over time as the context is developing. The control network implements a set of executive mechanisms affecting the propagation of activation in representational network. „Control network is thought to support working memory and executive representations that encode information about the temporal, situational and task context relevant to the current behavior." (Ralph et al., 2017).

2.1.2.1 Neural corelates of automatic and controlled semantic retrieval

Supportive evidence for two different neural networks (bottom-up and top-down) responsible for automatic and controlled retrieval process was also provided by Whitney and colleagues (2009), who showed that the processing of strongly semantically associated words induces the activation in distinct brain network including bilateral angular gyrus (AG) and rostromedial prefrontal cortex (rMPC). However, processing of ambiguous words recruiting cognitive control, resulted in an increased activation of LIFC. This region can be subdivided into anterior and posterior left inferior frontal cortex (aLIFC and pLIFC). PLIFC employment has been shown in pre-retrieval processing and its recruitment has been emphasized during situations demanding on controlled access to meaning of words. This region has been suggested as neural substrate supporting strategic search for relevant semantic concepts. ALIFC has been proposed as a neural substrate engaged in post-retrieval selective processing. This structure is responsible for top-down regulation and resolving of competition among ambiguous retrieved concepts.

The engagement level of bottom-up or top-down network is determined by familiarity with the context and cues accessible at the time. The more familiar we are with the context in which information is usually encoded, the smaller input representation network needs to response properly. If the context of a task requires suppression of automatic responses (i.e. representations that contain atypical features, or if the retrieved information is encoded weakly), the input from control network must be stronger. There is no strict asynchrony in activation between activation of associative retrieval network (AG and rMPC) and control retrieval network (aLIFC and pLIFC), but the proportion of their activation is rather context-dependent. In everyday life, you can use automatically retrieved concepts and compare them to those retrieved by controlled strategic search followed by post-retrieval selection process. Therefore, associative and controlled semantic retrieval should be viewed on continuum spanning from network of AG and rMPC, active mainly in automatic semantical associations, to aLIFC and pLIFC, responsible for exhaustive and goal-directed controlled retrieval (Whitney et al., 2009). Comprehensively, LIFC is proposed as crucial neural substrate for cognitively controlled semantic retrieval, since it executively guides and manipulates activation of representations network, where semantic knowledge is stored.

2.1.2.2 Functional connectivity of LIFC

Complex interconnectivity is natural property of brain and different regions are sharing functional properties. In context of LIFC, responsible for controlled semantic retrieval, we have to be precise in description of its functional connections with other areas. Functional connectivity differs from anatomical connectivity. Functionally connected areas in brain are those, among which statistical covariance of activations can be observed. Activity level of brain areas oscillates over time and effective connectivity describes impact of one area over another. Alternations of effective connectivity are associated with specific context of experimental conditions (Rowe & Frackowiak in Nadel, 2003). For examination of functional connectivity is used fMRI together with method called tractographic diffusion tensor imaging (DTI). DTI is based on fact that water in nerve fiber tracts diffuses asymetrically in direction of fibers. Using DTI we are able to trace direction of watter diffusion, which allows us to observe functional connected tracts. Concurrently, fMRI allows us to observe activity of brain areas and DTI provides us insight in their functional connections with rest of brain structures.

Processes and brain computations involved in semantic retrieval and language are overlapping in substantial extent. Language network (LN) in left frontal lobe has been suggested to consists of Brodmann´s areas 44, 45, 47 and ventral part of 6 (see Fig. 2) (Hagoort, 2005). LN can be recruited by two other brain networks, default mode network (DMN) and executive network (EN), between which we can observe strict anti-synchrony in activation. For example, in daydreaming without any specific task, language is recruited by DMN in form of internal speech. On the other hand, purposefully explaining certain topic in front of audience of listeners will require employment of EN (Aboitz, 2017). EN recruits LN to systematically and strategically retrieve semantically relevant words from memory. In context of semantic processing, there have been identified two ways, dorsal and ventral, projecting to Brodmann´s areas 44 and 45. Dorsal pathway is processing phonological, articulatory and syntactic information, whereas ventral pathway serves to identification of speech sounds. Ventral pathway is crucial for associating incoming inputs with stimuli from long-term semantic memories. „Accordingly, while the more posterior part of Broca's area (area 44), which is connected to the dorsal pathway, has a role in phonological fluency and grammatical processing, the anterior Broca's region (area 45), which is more connected to the ventral pathway, is more related to associative processes and memory retrieval" (Aboitiz, 2017). Ventral stream connected to aLIFC is supposedly neural tract in brain providing necessary neural connections, responsible for proper functioning of semantic retrieval. Ventral stream should be in context of this work described in anatomically precise manners. Ventral pathway contains fibers along the superior temporal lobe, through auditory area and connecting them with anterior temporal lobe and finally attaching to Brodmann´s areas 45 and 47, making up anterior part of LIFC. Auditory regions in anterior temporal lobe also play important role in semantic processing. Connection of these area is built up from inferior longitudinal fasciculus and inferior fronto-occipital fasciculus. To this connection is referred as a ventral pathway for language (see segmented arrows in Fig. 3) (Aboitz, 2017).

2.1.2.3 Language and LIFC

A number of studies indicate that the processes and brain computations involved in semantic retrieval and language are largely overlapping (Hagoort, 2004; Hagoort, 2005;

Cerruti & Schlaug, 2009). Associative words are therefore produced effortlessly but dissociative words require greater effort. LN, brain network responsible for producing and comprehending of language, presumably incorporates LIFC, since language would be useless without retrieval of semantically relevant representations from memory. Combination of separable independent elements into a coherent representation, such as in language, is called binding. It is related to processing of information in different cortical areas and at different time scales. Unification process taking place on semantic, syntactic and phonological level of language, retrieves information from memory and combine them in units. Neural tissue responsible for unification must be able to actively maintain information online. PFC plays important role in integration of information in time-span required for retrieving and selecting from appropriate alternatives. According to localization of language network, LIFC is plausibly part of prefrontal cortex relevant for unification in language (Hagoort, 2005). Based on findings of Indefrey & Cutler (2004), LIFC is neural substrate responsible for unification into general representations by engaging lexical information stored in temporal lobe involved in lexical processing. LIFC is assumed to be critical node providing space for unification in interaction with superior temporal gyrus. Semantic unification seems to be engaged in establishing of sense and reference of utterance, what is also supported by study of Hagoort et. al. (2004), where increased BOLD response of LIFC area was observed in processing of sentences with incorrect information and semantic oddities.

Broadly speaking, LIFC is proposed to be involved in more language domains and Brodmann´s areas (44, 45, 47, 6) are specialized for language processing, even though overlap of their activation can be observed (Fig. 4). Brodmann´s area 47 and 45 are involved in semantic processing, areas 45 and 44 provides syntactic processing followed by areas 44 and 6 being responsible for phonological processing. LIFC is vital for unifying lexical and non-linguistic information. Non-linguistic information could be gestures, but also conceptual knowledge stored in semantic long-term memory. In process on retrieving of linguistic information, we are referring to phonology/phonetics, syntax, features such as grammatical gender, word class (verb, noun, etc.) and also conceptually specific words (Hagoort, 2005). These processes are crucial for resolving inference between interferences among actively maintained words holded in working memory (Badre et al., 2005).

3 Brain stimulation

Brain stimulation or neurostimulation is a set of scientific methods enabling an experimental manipulation of brain processing. Such methods provide causal evidence concerning the link between the brain and behavior. Neuromodulation refers to modulation of physiological functioning of neural tissue. Modulation can be delivered to particular brain region via an induction of electric or electromagnetic fields. Different ways of brain stimulation results in various effects (Reti, 2015). Neurostimulation is often used in brain research in order to obtain a causal insight into the engagement of brain regions in specific cognitive tasks. Clinically, neurostimulation technology enhances functioning of deficits caused by paralyzed neural tracts, helps in the treatment of impairments related to sensory organs and also to chronic pain (Jacobson, 2017). In the following chapter, we will devote our attention to a brief introduction of brain stimulation techniques and their segmentation, Subsequently, we will specifically focus on transcranial direct current stimulation (tDCS) and it´s potential usage in stimulation of LIFC.

Historically, first attempt to modulate brain functioning via induced electric current belong to electroconvulsive therapy (ECT). ECT involves inducing of brief pulses of alternating polarity to provoke a grand mal type seizure within the brain promoting therapeutic effect. Intensity of delivered stimulation is about 800mA, however it is always optimized for seizure threshold of certain patient. In contrast, magnetic seizure therapy (MST) via magnetic coil delivers electromagnetic impulses in high frequency also result in in seizures. ECT and MST induce seizures followed by therapeutic effects and prescribed to patients with neuropsychiatric conditions resistant to pharmacological treatment or psychotherapy (Reti, 2015).

Stimulation techniques can be invasive or non-invasive, depending on whether it comes into direct contact with neural tissue or not. A good example of an invasive technique, i.e., a technique directly stimulating neural pathways via implanted electrodes, is deep brain stimulation (DBS). Nowadays, DBS is mainly used in the treatment of three neurological conditions (Parkinson’s disease, Essential tremor, Dystonia). According to patient’s diagnosis, target regions are individually mapped using MRI scans, followed by surgically implanted electrodes in the brain and connected to the pulse generator, implanted in chest area below the collar bone. DBS is invasive technique and because surgery is complicated, this treatment is used, when other ways of treatment, such as pharmaceutical, are not effective anymore (Reti, 2015). On the other hand, various non-invasive brain stimulation (NIBS) techniques use stimulation tools, which don´t come into direct contact with revealed brain tissue. For instance, transcranical magnetic stimulation (tMS) and transcranial electric stimulation (tES) should be mentioned (Carter, 2019). In case of NIBS, electrodes or magnetic coils are attached to the head. TMS uses single, paired or repetitive changes in magnetic field and via electromagnetic induction lead to changes in electric current in affected brain areas. TES uses current stimulation delivered through electrodes attached to head and current can be direct (tDCS) or alternating (tACS). NIBS do not cause any seizure or cognitive impairments and therefore these techniques became widely used as experimental tool, which has been increasingly used in recent years. Also, from clinical perspective, the devices and technologies that deliver brain stimulation have emerged as both tools to probe brain function and as therapeutic options for patients with neuropsychiatric disease, who fail to respond or cannot tolerate other therapies or medications (Reti, 2015).

3.1 Non-invasive brain stimulation (NIBS)

In contrast to DBS, NIBS techniques do not require direct contact with the brain tissue. TMS and tES are widely experimentally used and studied for their potential to broaden current state of knowledge in field of neuroscience. TMS uses electromagnetic induction in a way, where electric pulse in a coil induces a change in magnetic field. Those changes are, at right angles from coil and through the skull, inducing a magnetic field in the brain leading to depolarization of neurons (Reti, 2015). There is also rtMS, where „r“ stands for repetitive and rtMS seems to have long-lasting effects in terms of boosting or inhibiting synaptic motor cortex activity (Huang et al., 2005).

Cortical excitability can be non-invasively modified also by tES inducing electric field. In tES techniques current delivered conventionally do not exceeds 1–2mA. Higher current intensities usually result in higher adverse effects, including itching, burning and pain sensation on the skin under or around electrodes (Liu et al., 2018). When electrical current is applied via tES techniques, there are also physiological barriers leading to impedance. The first, and also the main barrier for tES in reaching brain tissue, is the skull. Skull has a high resistance (~160 Ωm). The second factor, impeding tES in its aim, is low resistance of the scalp (~2 Ωm). Important aspect of scalp resistance is that more than 75% of the current applied on it is seeking the path of least resistance. Therefore, this fraction of current is looking for shortcuts across the scalp (Vöröslakos, 2018). Resistance of these two barier is combined in tES and they have to be taken in consideration in using of tES (Haueisen et al., 1997).

In contrast to tMS, which stimulates depolarization of cells and therefore to production of action potential, tES influences membrane potential of brain cells in different fashion. TES affects polarization of neural cell membrane, which makes them more or less likely to fire action potentials, when another (e.g. internal) input is delivered. Specific cognitive task elicits activation of certain brain area (target brain area). TES can be used to bring target area in to ready-like state, which is in turn reflected by increase/decreased performance. Anodal or cathodal stimulation can be used in tES. Anodal stimulation leads to increase of neuronal firing frequency and cathode, with reversed current flow, leads to hyperpolarization of neural cell´s soma and therefore to decrease of action potential firing rate (Reti, 2015).

3.1.1 Transcranial electrical stimulation (TES)

Looking more closely on hypothesized effect of tES on brain processes, we need describe five mechanisms of its electrically induced effects on brain processing. These tES effects interact with endogenous activity of brain and operate simultaneously in various brain networks. In following section, we will devote our attention to those mechanisms. This first mechanism relates to excitatory and inhibitory postsynaptic potential (EPSP, IPSP). Postsynaptic potentials (PP) pasivelly moves along dendritic membrane and become gradually smaller as they spread. EPSP and IPSP are added together and those delivered spatially further from axon hillock contribute less to this sum, which results in hyperpolarization of membrane or to depolarization leading to action potential. TES, as exogenous factor, is also added to PP. Even very small changes in electric field, induced by tES, has potential to influence probability and timing of spike generation (Liu et al., 2018). „1 mV/mm in the extracellular space is sufficient to affect the discharge probability of cortical neurons“ (Ozen et al., 2010). This is known as “stochastic resonance” (Geisler & Goldberg, 1966).

Second mechanism by which tES operates is called rhythm resonance. Very weak electrical field can be timed to neural depolarizing phase. In general, this could be easily seen in controlled closed-loop conditions. In case, when there is no closed-loop system, we can still use application of weak alternating current at the same frequency as regular endogenous rhythm. There are various regular internal rhythms that could be recorded, for example by EEG. Externally via tES we can affect native oscillations at the similar phase (Liu et al., 2018). Some studies even suggest that neurons are able to synchronize to weak electric field even below 1 mV/mm (Francis et al.; 2003).

Third mechanism, called temporal biasing of spikes, is related to spike timing of neuronal subset. Via application of strong rhythmic fields, membrane potential is affected, and spike timing follows this change. Exogenous and endogenous polarization cooperates and therefore this is related also to mentioned mechanism of stochastic resonance. But strong rhythmic fields result in more reliable activation of the same neuron over many trials (Liu et al., 2018).

Fourth mechanism, network entrainment, works in a way, where certain activity patterns delivered via field induction, are targeted and entrained. Occurrence frequency of these patterns on EEG recording differs. The lower the occurrence frequency is, the stronger external stimulation has to be delivered. Native brain rhythms act in this context as competitors (Ozen et al., 2010).

Finally, tES can be used to impose a desired pattern of brain activity. This mechanism, however requires the strongest stimulation intensity among the others, as in this case TES is used to enforce a certain pattern over others. When tES is used to enforce arbitrary pattern, such as externally induced alpha activity on a network with an endogenously recorded tetha rhythm, field has to be stronger than in previous four mechanisms (Liu et al., 2018).

Two main tES techniques, tACS and tDCS, are widely used by researchers now days. Transcranial alternating current stimulation has also specific form called random noise stimulation (tRNS). Both, tACS and tRNS are techniques noninvasively modulating neuronal membrane potentials via oscillatory electrical stimulation with specifically determined or random frequencies interacting with rhythmic cortical activities. TACS induces alternating current flow with oscillation frequencies between 1 and 100 Hz, situated within the EEG frequency spectrum and modulating spontaneous cortical oscillations. Conceptually, stimulation frequency should match previously measured brain waves or rhythms typical for certain brain function. However, stimulation at higher frequency range (140 - 600 Hz) leads to alternations in neuroplastic excitability. TRNS stimulation protocol is substantialy particular type of tACS with random frequency, also called white noise.

TRNS in certain frequency range (101 and 640 Hz), has been shown to consistently increase excitability for about 60 minutes after stimulation and therefore to induce neuroplasticity (Terney et al., 2008). TACS and tRNS are applied to brain in order to get a better insight in relation between attributes of stimulus and biological effects. (Paulus, 2011).

3.1.1.1 TDCS

TDCS is a special case of tES in which direct constant currents are delivered into the brain using scalp electrodes (i.e., non-invasive). The induced currents that penetrate into the brain modulate its physiological properties. In contrast to TMS, which is used to deliver strong magnetic pulses resulting in activation of the underlying neuronal tissue (i.e., neuronal firing), tDCS utilizes weak currents, which doesn´t induce action potentials. In a tDCS stimulation, the current strength does not typically exceed 2 mA.

The physiological effects have been investigated in seminal works by Nitsche and Paulus in 2000 at University of Göttingen, where they started to examine low levels of electrical brain stimulation and their effects. Their studies shown that in order to induce a reliable physiological, cognitive or behavioral after-effect, stimulation intensity of 0.6 mA and stimulation duration of at least 5 minutes are required. It has been demonstrated that anodal tDCS leads to subthreshold depolarization in the area of interest, whereas cathodal tDCS leads to an opposite effect, i.e. hyperpolarization of neurons (Nitsche & Paulus, 2000 in Paulus, 2011). Therefore, an important aspect of tDCS lies in specificity of its polarity, since anodal and cathodal stimulation delivers opposite intracortical effects (Nitsche et al., 2005). In case of tDCS, the duration of stimulation is very important, since it may influence the outcomes in a non-linear fashion (e.g., prolonged stimulation can reverse the effects of anodal and cathodal stimulation). Notably, longer stimulation doesn´t necessary induce longer after-effects.

We can observe two kinds of effects of anodal tDCS: online (while stimulation lasts), offline/after-effect (after stimulation). Explanation for online neurophysiological effects induced via anodal tDCS is suggested by study on motor evoked potentials (Nitsche et al., 2003). Anodal tDCS leads to activation of NA+ voltage-dependent ion channels, which subsequently results in depolarization of neuronal membrane. After-effects are posited to be caused by activation of glutamate N-methyl-d-aspartate receptors followed by increase in postsynaptic CA++ concentration resulting in cortical plasticity (Nitsche & Paulus; 2000).

3.1.1.2 TDCS and semantic retrieval

Recent metanalytic review of Joyal & Fecteau (2016) concludes that tDCS can effectively modulate various aspects of semantic processing targeting the frontal, temporal, and parietal brain areas. Results of review supports suggestion that tDCS over frontal cortex is crucially involved in producing categoric words, processing of semantic ambiguities together with detection of semantic anomalies. The authors report a significant effect in 23 out of 32 experimental studies applying tDCS over the frontal cortex, and in 6 out of 9 experiments using tDCS over temporal-parietal cortices (Joyal & Fecteau; 2016). Also, metanalytic review by Binder (2009) supports that anodal stimulation over LIFC has been shown to affect semantic processing in healthy participants. These findings clearly indicate, that tDCS over LIFC can elicit modulatory changes in semantic processing.

Importantly, it has been shown that the application of tDCS over LIFC can substantially affect semantic retrieval. An influential study has indicated that anodal tDCS over LIFC enhances semantic fluency (Cattaneo et al., 2011). Also, with anodal tDCS over LIFC, shorter reaction times were required for decision, if words are semantically related (Ihara et al., 2015). Furthermore, experimental evidence posits that cathodal stimulation over LIFC (i.e., cortical inhibition) can lead to an altered semantic processing when retrieving uses of various objects: the stimulated individuals were able to generate more uncommon uses of everyday objects. Interestingly, this effect was not present when the participants produced common uses of objects. This evidence indicates that the inhibition of cognitive control during semantic processing can result in a specific improvement in terms of semantic flexibility and creativity (Chrysikou et al., 2013). Also, a recent study by Marko and colleagues (2018b) demonstrated, that anodal tDCS over left dlPFC can improve semantic inhibition (i.e., the ability to suppress dominant but inappropriate word associates). Overall, evidence from various studies suggests, that anodal tDCS over the left PFC may modulate distinct processes that participate in various word generation tasks (Joyal & Fecteau; 2016). Importantly, recent study of Pisoni and colleagues (2018) also suggests, that anodal tDCS particularly influence task-related networks, which are active during stimulation. Accordingly, even if induced stimulation spreads away, its functional effect is constrained to areas activated during stimulation. This indicates that tDCS can induce neuroplastic changes only in the areas involved in the processing during task. Thus, although the electric current delivered using tDCS have low anatomical specificity, the functional effects are not restricted only to the brain areas under the electrode but can also affect functionally connected nodes of larger-scale brain networks. Cortical activity elicited during task is working as endogenous specifier of functional enhancement delivered via anodal tDCS (Pisoni et al., 2018). Therefore, it has been proposed that even local stimulation can propagate to the functionally connected brain regions that underpin the specific cognitive function that is currently engaged.

In process of semantic retrieval, several associative and dissociative retrieval functions can be differentiated. To our best knowledge, process of semantic retrieval was not sufficiently addressed from this perspective. In current state of knowledge, it is not clear, which pre-retrieval and post-retrieval mechanisms are influenced by anodal tDCS. We decided to address this issue in our project and for this reason, specific task demanding on automatic associative and controlled dissociative word retrieval was used together with anodal tDCS over LIFC area.

Research problem

The current state of the knowledge in area of semantic processing indicates that LIFC is a vital neural substrate responsible for retrieval from semantic memory. In scope of semantic processing, substantial amount of evidence supports the assumption that LIFC serves primarily for purposes of semantic retrieval. However, just little research attention has been devoted to a more fine-grained differentiation of semantic retrieval. Nature of involvement of different pre-retrieval and post-retrieval mechanisms is not clear. It is presumably possible, that neurostimulation techniques may differently affect particular mechanisms of semantic retrieval. In aspiration to answer this question, we decided to devote our research attention to how specific functions of semantic retrieval could be affected by anodal tDCS. Aim of our project is to address this question with anodal tDCS over LIFC in inonvative word-production task enabling us to differentiate between several retrieval functions. We will specifically focus on anodal tDCS over LIFC in context of automatic associative and controlled dissociative retrieval. This differentiation is valuable for broadening of current understanding of semantic retrieval and its neural underpinnings. If LIFC is employed in controlled pre-retrieval activation of appropriate semantic representations, we expected that tDCS over this region would improve associative retrieval measures (i.e., tDCS over LIFC will enhance the top-down signal that supports semantic activation of associates). On the other hand, if LIFC is employed in controlled regulation of semantic retrieval (i.e., inhibition), we expected that anodal tDCS in this area would improve performance in dissociative task (i.e., improved cognitive control will improve the ability to disentangle from habitually activated semantic representations).

Methods

Participants

Total number of participants was 27, from which 17 were females and 10 were males. Mean age was 23,37 (mode = 21), ranging from 20 to 30 years. Participants were native Slovak speakers and all of them were right-handed (mean score of Edinburgh Handedness Inventory was 50 or higher; Veale, 2014), and native Slovak speakers. Participants were selected following an anamnestic assessment in order to select those, who have not experienced psychiatric issues nor neurologic disorders in the past and were not using any medication throughout the duration of the experiment. Only individuals with no history of neurological or psychiatric disease, neuropharmacological treatment, or brain injury were allowed to participate in the study. A financial compensation (25 EUR) was provided for completing experiment. Crucial information about experiment was provided in written form to all participants, where they were informed about aspects of project, that may cause some discomfort. All participants signed written informed consent at the beginning of the first session and the experiment was approved by the local research ethics committee and conducted in accordance with the Declaration of Helsinki. All participants visited the lab three times, because our experiment was part of larger research project. On each session, probands were assessed in three different stimulation conditions (tACS, tDCS and sham) in a balanced order. Only two experimental sessions were considered and evaluated in this thesis (tDCS and sham). All of participants tolerated stimulation without any serious problems.

Experimental design and procedure

All subjects participated in three experimental sessions. Sessions were separated at least by five days in order to avoid potential carry-over effect. At the beginning of experimental procedure, participants completed a short questionnaire assessing their situational emotional state, such as motivation, fatigue and mood, using self-reported measures. This assessment was present to ensure the psychological state of participants was comparable across experimental conditions and to confirm that these factors did not confound experimental findings. Using Likert scales, participants indicated the extent of various adjectives, that described situational psychological states and emotions (drowsiness, exhaustion, fatigue, satisfaction with their concentration, motivation to task fulfillment, irritation, frustration, interest in task). Chronological description of procedure is following: after fulfilling assessment concerned about situational psychological states and emotions of participants, they completed a computer-based lexical-semantic task consisting of a repeated (within-subject) experimental design including three main factors of interest:

1. tDCS/Sham

Participants obtained either tDCS or sham condition. In the sham condition, the current was ramped up for 15 seconds, in order to induce skin sensation mimicking real stimulation. The current intensity was thereafter ramped down and the stimulation stopped. In the active tDCS condition, the current ramped up for 15 seconds, which was followed by 480 seconds of stimulation, during which participant was seated and rested without any particular task given. After this resting phase, assessment in experimental task started. Participants had 660 seconds to finish the task followed by rump down of current lasting 15 seconds. In case of slower performance of participants, stimulation could last for 120 seconds longer subsequently followed by rump down lasting 15 seconds (see schema on Fig. 5). Cap used for the precise localization of the targeted area (LIFC), which was in accordance with the 10-10 EEG system of electrode placement. Anodal electrode of size 25cm² was attached to head in between F5, F7, FC5, and FT7 site, and a larger referential electrode of size 35cm² was placed on contralateral side in between Fp2, AF4, AF8, F6, and F8 sites (Fig. 6). Intensity of delivered current was 2mA and impedance of attached electrodes was ensured to be below 7 kΩ.

2. Block (Baseline, Online, Offline)

The participants completed three separate blocks of lexical-semantic assessment: before the stimulation (baseline), during the stimulation (online), and immediately after the stimulation (offline). Assessment of online block always started after 480 seconds of stimulation and lasted maximally 780 seconds.

3. Lexical-semantic assessment

Semantic memory retrieval was assessed using a modification of the Associative chain test (ACT; Marko, Michalko, Riečanský, 2018a). The cognitive assessment of retrieval parameters involved two separate blocks, each having several discrete conditions (i.e., rules of production). The first block involved continuous word production mode including three discrete conditions in the following order: (1) category retrieval (also referred to as category fluency), (2) associative retrieval, (3) dissociative retrieval, and (4) alternating associative-dissociative retrieval. The second block involved discrete word production (single response) having three randomly presented conditions: (1) associative, (2) dissociative, and (3) random word production.

In the category retrieval condition, participants were given a category determinant (e.g., “Food”) and asked to produce as many words as they could in 60s (since the performance in this part was time constrained, the amount of responses differed across individuals, sessions, and blocks). In the associative condition, participants were asked to produce 20 semantically related words in a way, that each new response had to be semantically related with the previous one (e.g., Forrest [prime word] ← Tree ← Wood ← Table ← Pen). In the dissociative conditions, participants produced words that are semantically unrelated (e.g., Statue [prime word] ← Soup ← Hammer ← Feather ← Honey). The dissociate chain included 20 trials/responses.

The second block of ACT includes retrieval of discrete words (one response) in three randomized conditions: association, dissociation and random word production. The participants were asked to deliver a suitable word response as quickly as possible (e.g., Pen [A] ← Paper [response] - Suit [D] ← Fork [response] - Power plant [D] ← Dictionary [response] - Electricity [A] ← Light [response] - ***** [R] ← Aquarium [response] - Bird [D]). For each word (N = 20 per condition), participants were required to provide both an associative and a dissociative response (the instruction was counterbalanced within each block). Each produced word was assessed for response time.

We also accounted for extent in to which participants felt unpleasant feelings related to tDCS stimulation, that may occur at the beginning at rump up of stimulation. After adjusting the headset and turning on the stimulation, administrator always asked participants, how intensively, on scale from 1 – 5 (very weak – very intensive), can they feel itching, pinching, burning or pain. At the end of the online block participants were also questioned, how intensively on scale 1 – 7 (very weak – very intensive) they personally judge the intensity of stimulation.

Analysis

The total number of responses provided by each participant in each ACT condition was 240 (20 chain block + 20 random block) * 3 (3 times repeated - baseline, online, offline)* 2 (since there were two experimental sessions).

We removed word responses with extreme latency (RTs >20s). This removal was done before the statistical analyses (less than 0.05% of responses were removed this way). Also, less than 5% of responses from dissociative condition was removed as considered inappropriate (i.e., semantically related), as indicated by four trained raters. The independent raters achieved high agreement in this process (inter-rater agreement > 0.85)

Analysis was done in R (R Core Team, 2018). With regard to some outlying observations, which exceeded ± 1.5 of interquartile range, we performed winsorization of data (10% two-sided quantile cut-off) prior statistical computations. The respective lexical-semantic retrieval RTs were modeled as a function of Testing block (baseline, online, offline), tES (sham, active), and their interaction. Computation of linear mixed effect models (LMEM; lme4, Bates et al., 2015) was done in order to take in to account measurements nested within proband via estimation of random intercept (unstructured covariance matrix). The LMEM models were evaluated using restricted maximum likelihood (REML) and p-values were obtained using Satterthwaite approximation for degrees of freedom, which is optimal for small research samples (Luke, 2017). Tukey HSD adjustment was used for correction of post-hoc p-values.

Results

No differences in fatigue, motivation, and mood were observed between the sham and active tDCS session. These factors did not vary significantly and remained relatively constant across repeated experimental sessions (Tab. 1).

Table 1

Situational psychological factors

Repeated measures ANOVA with Greenhouse-Geisser correction

Source		Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Stimulation	Fatigue	0.180	1/24	0.180	0.029	0.867	0.001
	Frustration	0.020	1/24	0.020	0.057	0.814	0.002
	Motivation	0.080	1/24	0.080	0.129	0.723	0.005

Note. Situational psychological factors across experimental session did not significantly differ.

Before we begin to introduce our statistical results, we need to introduce a baseline model of reaction times. To create this model, we utilized linear mixed effect model (LMEM) for analysis of data gathered in performance of lexical-semantic task before stimulation (i.e., baseline block). Execution of this analysis enabled us assessment of differences between dissociative and associative type of tasks and the difference between fixed and alternating type of tasks without impact of tDCS. Substantial effects were discovered with a LMEM analyses for both, the Response type, $\chi2(1) = 1358.20$, $p < .001$ and the Sequence type, $\chi2(1) = 130.0$, $p < .001$ (see Tab. 2). Even interaction of response and sequence type was significant $\chi2(1) = 26.11$, $p < .001$. Figure 7 depicts the significantly greater reaction times of the dissociative condition compared to associative condition (inhibition cost). Response latencies of associate and dissociate in alternating condition increased, however significantly only in dissociative responses (switching cost). According to data, lowest reaction times belongs to category retrieval condition.

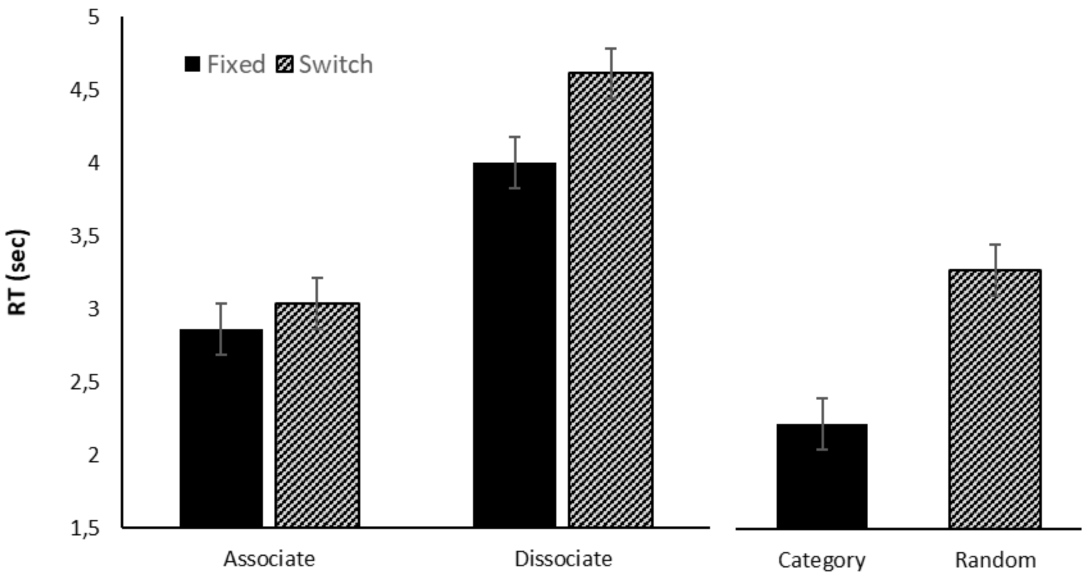


Figure 7. Baseline model for ACT conditions. The figure depicts the average response time (RT) of word production by distinct ACT conditions. Error bars represent +/- 1 SE. RT´s in random block are presented as second, fourth and sixth bar from left. In a graph word "switch" points to aspect of the random block, that probands had to dynamically switch between associations, dissociations and without-start word condition.

Table 2

Baseline model for ACT measures

Linear mixed effect model		
Response type (associative vs dissociative)	F(1,5868) = 1358.20	p < 0.001
Sequence type (fixed vs alternating)	F(1,5868) = 130.00	p < 0.001
Response type x Sequence type interaction	F(1,5868) = 26.11	p < 0.001

Note: the results describe the effects of different ACT conditions on RT in the baseline assessment blocks (i.e., before stimulation) across the experimental sessions.

Following the baseline model, we investigated the effects of tDCS on semantic retrieval. A separate LMEM was computed for each retrieval measure, including associate RT, dissociate RT, category RT, and random RT. All LMEM models included two main factors (tES, Block) and their interaction, which was the main focus of our hypothesis testing. The overall amount of responses we worked with was 2534 for categoric fluency, 6077 for associate, 5844 for dissociate and 3040 for the random condition.

A LMEM for associative condition (Tab. 3) indicated a non-significant interaction between tES and block, $F(2, 6047.2) = 1.055$, $p = 0.347$. Significant interaction of tES and block was observed for categoric fluency (Tab. 4). $F(2, 2508.1) = 5.1791$, $p = 0{,}005$. Another statistically significant interaction was indicated by the LMEM for dissociative condition (Tab. 5), $F(2, 5813.5) = 4.424$, $p = 0.012$. The interaction between tES and Block was not significant for random condition (Tab. 6), $F(2, 3009.7) = 1.65$, $p = 0.192$. All of these results are depicted in Fig. 8.

As we can see from results, in associate condition, there was statistically non-significant improvement in RT´s regarding task performance. Associative (Tab. 3) and random condition (Tab.6) are suggesting online and offline improvement in associative and random word production, although statistically non-significant. In case of categoric fluency (Tab. 4), results are showing statistically significant improvement in online condition, but slight decrease in performance observed in offline condition. In case of dissociation (Tab. 5) overall improvement in performance was observed, but only in case of offline condition we can say that this improvement was statistically significant.

Table 3

Associative retrieval

Linear mixed effect model

Effect	NumDF	DenDF	F	*p*	
Block	2	6047,2	13,7574	1,09E-06	***
tES	1	6050,6	6,8187	0,009043	**
Block:tES	2	6047,2	1,0557	0,347996	

Note. RT´s were non-significantly shorter for online and offline condition.

Table 4

Categoric fluency

Linear mixed effect model

Effect	NumDF	DenDF	F	*p*	
Block	2	2502,6	15,9674	1,29E-07	***
tES	1	2512,1	0,447	0,503823	
Block:tES	2	2508,1	5,1791	0,005693	**

Note. RT´s were significantly shorter in online condition, while non-significantly longer for offline condition.

Table 5

Dissociative retrieval

Linear mixed effect model

Effect	NumDF	DenDF	F	*p*	
Block	2	5813,5	37,9833	< 0.001	***
tES	1	5814,9	2,9347	0,08675	.
Block:tES	2	5813,5	4,4241	0,01203	*

Note. RT´s were shorter in both, online and offline condition, while only on results for offline were statistically significant

Table 6

Random retrieval

Linear mixed effect model

Effect	NumDF	DenDF	F	*p*	
Block	2	3009,7	13,49	1,47E-06	***
tES	1	3012,2	35,272	3,19E-09	***
Block:tES	2	3009,7	1,65	0,1922	

Note. RT´s were non-significantly shorter for online and offline condition

Based on deviations from baseline RT model, we can state changes in RT´s with stimulation (online) and after stimulation (offline). As shown in Figure 2, the active stimulation lead to improved retrieval performance (faster retrieval) in almost all measures and/or blocks. However, tES significantly improved only the category retrieval in the online assessment block and dissociative performance in the offline assessment block (both marked by a star in Fig. 8).

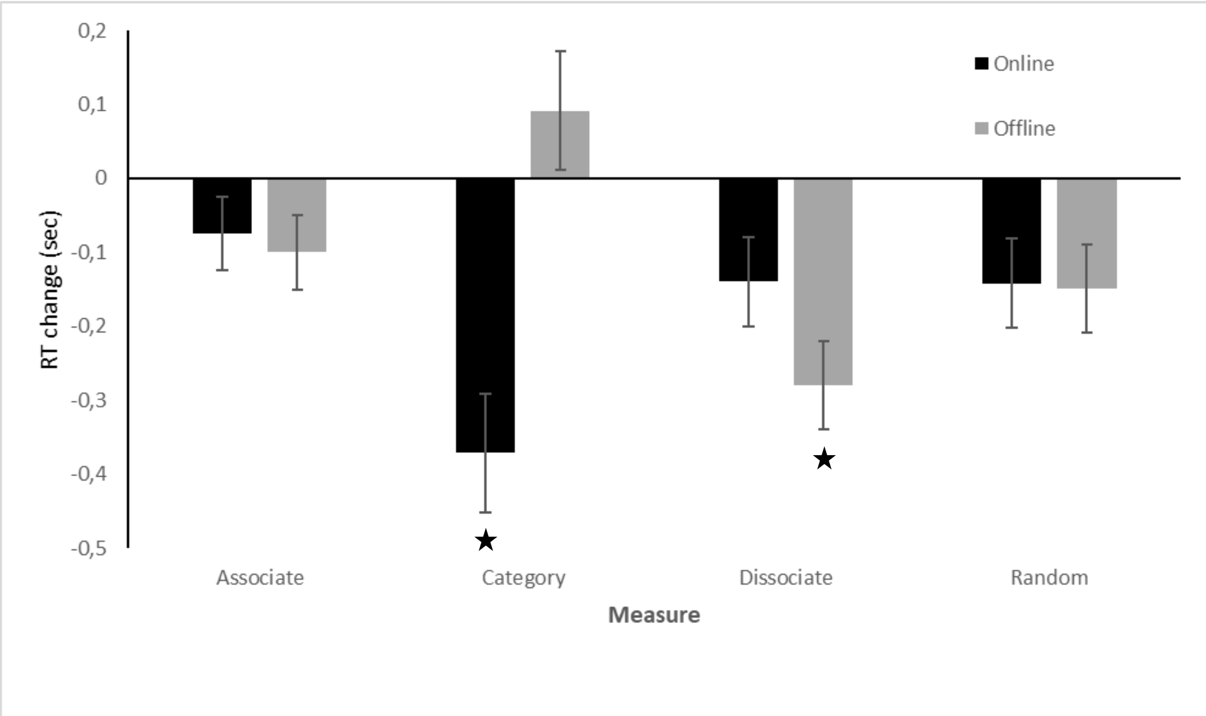


Figure 8. Bars represents contrast of the active condition against sham tES condition after controlling for the baseline performance. Values above the horizontal line indicate negative effect of tES (longer RTs) and values below the horizontal line represents improvement in the respective performance (shorter RT, as induced by active tES).

Disscusion

In the present study, we investigated the role of LIFC in automatic and controlled semantic retrieval using neurostimulation. For this purpose, healthy participants were assessed for automatic–associative and controlled–dissociative retrieval performance and received tDCS over left LIFC. These cognitive measurements were obtained prior to tDCS (baseline measurement), during tDCS (online), and immediately after it (offline). Under unchanged situational psychological states across experimental sessions, the results provided by our project indicate that anodal tDCS over LIFC area substantially affects lexical-semantic retrieval and processing. Moreover, we revealed that these effects critically depend on specific retrieval tasks. The strongest supportive evidence was found for categoric fluency (in the online block, when tDCS provided active concurrent stimulation) and for dissociative retrieval condition (in the offline block). Trend of improved performance in online and offline condition, was observed also in associative and random blocks of task. Overall, tES seems to have a positive effect on the performance regarding automatic and controlled lexical-semantic retrieval. Our findings are in line with the previous metanalytical reviews suggesting that tDCS over LIFC modulates semantic processing (Binder et al., 2009; Joyal et. al., 2016).

The effects of retrieval conditions

Regarding baseline model, there are a few attributes requiring explanation in further detail. The retrieval from semantic memory was fastest in the context with provided cue and without the necessity of cognitive control engagement. Obviously, shortest reaction time in baseline model was observed for category fluency (2.215 seconds; see second bar from the right in Fig. 7). According to Woods and colleagues (2015), simple reaction time is 213ms and considering our results we can conclude that approximately additional 2 seconds are needed for automatic semantic processing. In this task, automatic associative mechanisms are predominantly engaged. Also, in this condition primes words, which function as cues guiding semantic search for retrieval of relevant representations, are present. These representations do not require further cognitively controlled processing; however, it could be argued that prolonged retrieval from the same category can become increasingly demanding as the category exemplars are getting depleted. Thus, in the later phases, some support from cognitive control may be involved. In random condition (see first bar from the right in Fig. 7), on the other hand, no prime was provided to cue responses. Therefore, associative mechanism in random condition isn´t automatically retrieving representations, and thus longer time for response initiation is required. As indicated by the baseline level of performance in associate and dissociate conditions (first four bars from left in Fig. 7), reaction time for dissociate condition is substantially longer than for associate condition. This effect is in line with previous evidence (Marko et al., 2018; Collette, 2011), showing that dissociative performance may involve increased demands on executive control, from which we need to enumerate inhibition and switching.

Our observations indicate that an extra cognitive effort, as indicated by longer response latencies, is required during semantic dissociation. However, it seems that this effort can not be reduced to the effect of missing cues, as in random retrieval task, which also did not provide cue words for retrieval but did not lead to a substantial increase in RT when compared to associative retrieval speed (approximately +250ms). We therefore argue that the difference between dissociative and associative RT largely reflects cognitive control engagement.

In general, the system responsible for cognitive control is not employed by default and frequently as it slows cognitive performance and decision making. On the other hand, when the situation demands logical strategy, cognitive flexibility, and consciously guided action, effortful cognitive control system is engaged. This account is in line with Kahneman's (2011) second system, which is a part of his broader two-system conception. More specifically, the increased processing time and effort during dissociation as compared to association can be assigned to increased demands on controlled inhibition (i.e., inhibition cost). Inhibiting is a post-retrieval mechanism which serves to suppressing of automatic prepotent responses retrieved from semantic memory (Miyake et al., 2000). In the case of dissociative performance, prime words probe automatic associative retrieval mechanism, which leads to an effortless retrieval of various associated words from memory. However, due to the task instructions, these words have to be suppressed (meaningful semantic relationship is inappropriate due to instruction) and an engagement of strategic search for unrelated semantic content is employed. This whole process is reflected in extra time needed for response.

Switching is another aspect of cognitive control indicated by prolonged response latencies. In this case, longer response times reflect effortful recruitment of cognitive control mechanism devoted to dynamic switching between retrieval rules (i.e., associative and dissociative responses). As indicated in Figure 7, alternating the rules resulted in increased response times, which can be referred to as “switching cost”. The difference between fixed associations and fixed dissociations (first and third bar in Fig. 7) reflect only inhibition cost, whereas the difference between fixed and switching conditions (for both associative and dissociative resonse type, see Fig. 7) is due to switching cost. Interestingly, this switching cost was significant only in dissociative performance, not in associative performance, indicating that inhibition and switching may share or perhaps compete for a limited amount of resources that supporting cognitive control systems (Westbrook & Braver, 2015).

The effect of anodal tDCS over LIFC on retrieval

In line with the previous findings provided by Cattaneo and colleaugues (2011), we observed, that anodal tDCS over LIFC resulted in a convincing modulation of semantic retrieval. We propose that these effects were mediated by a tDCS-induced elevation of neuronal excitability in LIFC and the functionally connected brain network that support semantic memory retrieval. As a consequence of elevated excitability, the LIFC could shift to a “ready-like” state, which in turn facilitated the behavioral performance indexes. This modulation could be partially due to a non-specific, overall enhancement of semantic processing, which we found in our experiment (Fig. 8). However, only specific retrieval measures were significantly modulated, indicating that particular lexical-semantic processes may be suspectible to anodal prefrontal neuromodulaiton.

The associative performance was non-significantly improved in both blocks (during and after the stimulation). Improvements in generating associative chain of semantically related words were very subtle, facilitating the performance by approximately 75ms in online and 102ms in offline assessment. Response times from random condition yield a very similar pattern of effects, however, the improvement was slightly more pronounced and the difference between online and offline block was almost unobservable. Improvements of RTs in random condition reached 142ms in the online and 149ms in the offline condition. However, they were not statistically reliable.

Category fluency was the only condition, where we could observe a significant improvement during the stimulation (i.e., online effect; note that the offline effect was not statistically significant). In the online block, category retrieval performance was improved by 371ms, yielding a substantially large effect. Results for the dissociative condition indicated a trend (i.e., non-significant) towards improvement in the online block (140ms). Interestingly, this the effects reached statistical significance in the offline block, indicating a moderate improvement immediately after the stimulation (280ms). These results support the prediction that tDCS over LIFC would improve the controlled semantic processing, presumably due to increased excitability of the cortex or functional connectivity within the task-dependent network. This assumption is in line with research of Pisoni and colleagues (2018) proposing that anodal tDCS specifically modulates task-related functional networks that are active while delivering stimulation.

We expected that, if LIFC is involved in the controlled semantic processing (i.e., the selection and inhibition of lexical-semantic representations), tDCS over LIFC would substantially affect cognitively controlled dissociative performance, but not associative performance. On the other hand, if LIFC supports binding of semantic features, we would expect an improvement in associative performance but compromised dissociative function. From the gathered data it is clear, that distinct aspects of retrieval were affected by tDCS in different way. If the effects of tDCS could be attributed to a boost in the pre-retrieval mechanism supporting semantic activation of associates, we should observe substantial improvement in performance in both associative and category fluency condition, however this was not the case. Based on our evidences, we thus propose that tDCS over LIFC may only partially enhance pre-retrieval mechanism supporting semantic activation of associates. Following the string of thought, we observed significant improvements induced by stimulation only in categoric fluency retrieval and controlled dissociative retrieval, which unveil some intersection in their functionalities. We assume that direct current stimulation had a positive effect on controlled regulation of semantic retrieval, as indicated by increased performance in the dissociative offline block. Following these results, we propose that stimulation of LIFC boosted post-retrieval mechanism responsible for inhibition of prepotent habitually activated responses, which has facilitated flexibility of retrieval in this type of retrieval performance.

Regarding the functional intersection of category fluency with dissociative condition, a further explanation is necessary. According to Hurks and colleagues (2006), concurrently with the task we can observe hyperbolic decrease in word generating. During 60 seconds of category fluency task, more than a 50% of the words are produced in first half of the task. Automatic retrieval mechanism has presumably only a limited amount of resources (i.e., category cluster size), which can be activated effortlessly and after their depletion cognitive control mechanisms are recruited to strategically search for next relevant representations. We propose that tDCS may enhance category fluency especially in the later stages of the task (i.e., prolonged retrieval from the same category), when immediately available category instances and automatic associations are getting exhausted and a controlled strategic search for other relevant representation has to be engaged. However, further detailed research investigation regarding intersection of categoric fluency and controlled retrieval is needed.

Challenges for this explanation, provided by Flinker and colleagues (2015), suggest that task demanding on repeating and reading single words requires operation linking phonemic with motor sequences, but do not recruits semantic and syntactic processing. They also suggest that LIFC coordinates this linkage via “reciprocal interactions with temporal and frontal cortices responsible for phonemic and articulatory representations, respectively, including interactions with motor cortex before the actual act of speech“ (Flinker et al. 2015). It proposes that LIFC functions as a convertor, whose main function lies in transformation of phonology in articulation rather than to mere production of words (altoutht participants in our project typed the responses, a subvocal phonological articulation could be engaged when responding). We assume, that if this suggestion was valid, results of stimulation should affect all retrieval conditions in the same way, regardless of the semantic condition/rule, which was not the case (see Fig. 8). The significantly differente effects of tDCS on category fluency and dissociative condition leads us to refuse the alternative explanation that the modulation of LIFC reflects a mere converting from phonology to articulation. In the scope of our project, we are able to refuse this alternative explanation.

Limitation of our project stems from the fact, that we were not able to directly measure physiological effects of tDCS, especially the proposed effects on cortical excitability of the neural tissue in LIFC area or functionally related brain network. Although, increased excitability was assumed based on previous evidence (Pisoni et al., 2018), further studies using electrophysiological or neurobiological measures are required. Another limit of the present experiment stems from the fact that tDCS parameters were not optimized for every participant (individual physiologically-specific characteristics). Also, the methodological approach for lexical-semantic measurement involved a limitation as it did not address specific type of semantic responses and semantic relations between words (i.e., taxonomic versus thematic associations/relations (Mirman, 2017). Also, in order to decrease subjective bias, word pairs were assessed on semantical relationships by multiple administrators among which we observed high conformity. We propose that by adding more administrators we can get closer to a socio-cultural mean, of what is or isn´t semantically related. However, subjective experience of participants can´t be lowered with multiple administrators and some idiosyncratic meaningful semantic relationships perceived by participants may be overlooked. The future research in this area could also by improved by using advanced natural language processing methods of semantic analysis (i. e., *Lexical semantic indexing*, which is technique used for web search engine optimalization) (Dumais, 2005).

Finally, we need to address the aspects open for further investigation. It may be interesting if further studies address how LIFC is recruited in controlled semantic retrieval in bilingual participants. Since our project encompasses only natural Slovak speakers, interesting findings of brain corelates employed in retrieving of semantic meaning could be provided by comparison of retrieval in mother tongue and second language. Some scientific attempts in this direction have already considered LIFC as brain area involved in even ubiquitous domain-general processing (Coderre et al., 2016). LIFC activity is presumably boldly pronounced in recruitment of cognitive control and language processing. Further investigation of brain stimulation with respect to semantic networks is needed, undoubtedly. In line with this project further research would be needed in order to investigate the cognitive and neurobilogical overlap between category and dissociative retrieval. Our results shed light on the modulation of controlled semantic retrieval mechanism using anodal tDCS, which may promote later stages of category retrieval and dissociative performance. Although we were able to observe significant effects of stimulation in task, it is not clear, how long/short-lasting modulatory effect are. Detailed understanding of the temporal course of such effects and their persistence should be subjected to further study. Knowledge in the field of enhancing controlled semantic retrieval could be implicated in rehabilitation of neurological speech impairment (Monti et al., 2013). Notably, a large number of neuropsychiatric conditions involve compromised semantic cognition (Mirman & Britt, 2013), highlighting the need for of optimization of treatment protocols suitable for various neuropsychiatric disorders. To discover subtle, undiscovered and original semantic relationships is vital for various cross-sectional, interdisciplinary fields (design, engineering, science, art) demanding on focused and controlled semantic retrieval, therefore its also significant for every creative profession. Admittedly, in this field of study, great amount of questions remains to be unanswered. We introduced some ways, in which our findings can serve to potential upcoming research. Enhancing effects of anodal tDCS has prospects to bring advancement in understanding of brain structures responsible for controlled semantic processing.

Conclusion

Healthy participants were stimulated with anodal tDCS over left inferior frontal cortex and examined in task demanding on automatic associative and controlled dissociative semantic retrieval. Novelty of our approach stems from the methodology allowing us to a closer differentiation of semantic retrieval processes. Enhanced generating of semantically related words was observed in category fluency task and improved performance was observed in task requiring producing semantically dissociated words. Taken together, these results indicate that anodal tDCS over LIFC promotes controlled pre-retrieval and post-retrieval semantic processes. Thus, our results support and substantially extend the previous experimental evidence indicating an important role of left prefrontal cortex in controlled semantic memory retrieval.

Bibliography

Aboitiz, F. (2017). *A brain for speech: a view from evolutionary neuroanatomy*. London, United Kingdom: Palgrave Macmillan.

Badre, D., Poldrack, R. A., Paré-Blagoev, E. J., Insler, R. Z., & Wagner, A. D. (2005). Dissociable Controlled Retrieval and Generalized Selection Mechanisms in Ventrolateral Prefrontal Cortex. *Neuron*, *47*(6), 907–918. https://doi.org/10.1016/j.neuron.2005.07.023

Badre, D., & Wagner, A. D. (2002). Semantic Retrieval, Mnemonic Control, and Prefrontal Cortex. *Behavioral and Cognitive Neuroscience Reviews*, *1*(3), 206–218. https://doi.org/10.1177/1534582302001003002

Badre, D., & Wagner, A. D. (2007). Left ventrolateral prefrontal cortex and the cognitive control of memory. *Neuropsychologia*, *45*(13), 2883–2901. https://doi.org/10.1016/j.neuropsychologia.2007.06.015

Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting Linear Mixed-Effects Models Using lme4. *Journal of Statistical Software*, *67*(1). https://doi.org/10.18637/jss.v067.i01

Binder, J. R., Desai, R. H., Graves, W. W., & Conant, L. L. (2009). Where Is the Semantic System? A Critical Review and Meta-Analysis of 120 Functional Neuroimaging Studies. *Cerebral Cortex*, *19*(12), 2767–2796. https://doi.org/10.1093/cercor/bhp055

Bindschaedler, C., Peter-Favre, C., Maeder, P., Hirsbrunner, T., & Clarke, S. (2011). Growing up with bilateral hippocampal atrophy: From childhood to teenage. *Cortex*, *47*(8), 931–944. https://doi.org/10.1016/j.cortex.2010.09.005

Bozeat, S., Lambon Ralph, M. A., Patterson, K., Garrard, P., & Hodges, J. R. (2000). Non-verbal semantic impairment in semantic dementia. *Neuropsychologia*, *38*(9), 1207–1215. https://doi.org/10.1016/S0028-3932(00)00034-8

Caramazza, A. (1998). The Interpretation of Semantic Category-specific Deficits: What Do They Reveal About the Organization of Conceptual Knowledge in the Brain? *Neurocase*, *4*(4–5), 265–272. https://doi.org/10.1080/13554799808410627

Carter, R. (2019) *The Human Brain Book.* New York: DK Publishing

Cattaneo, Z., Pisoni, A., & Papagno, C. (2011). Transcranial direct current stimulation over Broca's region improves phonemic and semantic fluency in healthy individuals. *Neuroscience*, *183*, 64–70. https://doi.org/10.1016/j.neuroscience.2011.03.058

Cerruti, C., & Schlaug, G. (2009). Anodal Transcranial Direct Current Stimulation of the Prefrontal Cortex Enhances Complex Verbal Associative Thought. *Journal of Cognitive Neuroscience*, *21*(10), 1980–1987. https://doi.org/10.1162/jocn.2008.21143

Coderre, E. L., Smith, J. F., Van Heuven, W. J. B., & Horwitz, B. (2016). The functional overlap of executive control and language processing in bilinguals. *Bilingualism: Language and Cognition*, *19*(3), 471–488. https://doi.org/10.1017/S1366728915000188

Cohen, J. D. (2017) Cognitive Control: Core Constructs and Current Considerations. In Egner, T. *The Wiley Handbook of Cognitive Control*. Chichester, West Sussex, UK : John Wiley & Sons, 2017.

Collette, F., Van der Linden, M., Delfiore, G., Degueldre, C., Luxen, A., & Salmon, E. (2001). The Functional Anatomy of Inhibition Processes Investigated with the Hayling Task. *NeuroImage*, *14*(2), 258–267. https://doi.org/10.1006/nimg.2001.0846

Chrysikou, E. G., Hamilton, R. H., Coslett, H. B., Datta, A., Bikson, M., & Thompson-Schill, S. L. (2013). Noninvasive transcranial direct current stimulation over the left prefrontal cortex facilitates cognitive flexibility in tool use. *Cognitive Neuroscience*, *4*(2), 81–89. https://doi.org/10.1080/17588928.2013.768221

Dudukovic N. M. & Kuhl B. A. (2017) Cognitive control in memory encoding and retrieval. In Egner, T. (2017) *The Wiley Handbook of Cognitive Control*. Chichester, West Sussex, UK : John Wiley & Sons, 2017.

Dumais, S. T. (2005). Latent semantic analysis. *Annual Review of Information Science and Technology*, *38*(1), 188–230. https://doi.org/10.1002/aris.1440380105

Duverne, S. & Koechlin, E. (2017) Hierarchical Control of Behaviour in Human Prefrontal Cortex. In Egner, T. *The Wiley Handbook of Cognitive Control*. Chichester, West Sussex, UK : John Wiley & Sons, 2017.

Farah, M. J., & McClelland, J. L. (1991). A computational model of semantic memory impairment: Modality specificity and emergent category specificity. *Journal of*

Experimental Psychology: General, *120*(4), 339–357. https://doi.org/10.1037/0096-3445.120.4.339

Feldman, J. A., & Shastri, L. (2003). Connectionism. In L. Nadel (Ed.), *Encyclopedia of cognitive science* (Vol. 1, pp. 303–309). London: Nature Publishing Group.

Flinker, A., Korzeniewska, A., Shestyuk, A. Y., Franaszczuk, P. J., Dronkers, N. F., Knight, R. T., & Crone, N. E. (2015). Redefining the role of Broca's area in speech. *Proceedings of the National Academy of Sciences*, *112*(9), 2871–2875. https://doi.org/10.1073/pnas.1414491112

Francis, J. T., Gluckman, B. J., & Schiff, S. J. (2003). Sensitivity of Neurons to Weak Electric Fields. *The Journal of Neuroscience*, *23*(19), 7255–7261. https://doi.org/10.1523/JNEUROSCI.23-19-07255.2003

Garrard, P., Ralph, M. A. L., Watson, P. C., Powis, J., Patterson, K., & Hodges, J. R. (2001). Longitudinal Profiles of Semantic Impairment for Living and Nonliving Concepts in Dementia of Alzheimer's Type. *Journal of Cognitive Neuroscience*, *13*(7), 892–909. https://doi.org/10.1162/089892901753165818

Geisler, C. D., & Goldberg, J. M. (1966). A Stochastic Model of the Repetitive Activity of Neurons. *Biophysical Journal*,*6*(1), 53–69.https://doi.org/10.1016/S0006-3495(66)86639-0

Gonnerman, L. M., Andersen, E. S., Devlin, J. T., Kempler, D., & Seidenberg, M. S. (1997). *Double Dissociation of Semantic Categories in Alzheimer's Disease. Brain and Language, 57(2), 254–279.* https://doi.org/10.1006/brln.1997.1752

Hagoort, P. (2004). Integration of Word Meaning and World Knowledge in Language Comprehension. *Science*, *304*(5669), 438–441. https://doi.org/10.1126/science.1095455

Hagoort, P. (2005). On Broca, brain, and binding: a new framework. *Trends in Cognitive Sciences*, *9*(9), 416–423. https://doi.org/10.1016/j.tics.2005.07.004

Hart, J., & Kraut, M. A. (2007). *Neural basis of semantic memory*. Cambridge, UK ; New York: Cambridge University Press.

Haueisen, J., Ramon, C., Eiselt, M., Brauer, H., & Nowak, H. (1997). Influence of tissue resistivities on neuromagnetic fields and electric potentials studied with a finite element model of the head. *IEEE Transactions on Biomedical Engineering*, *44*(8), 727–735. https://doi.org/10.1109/10.605429

Huang, Y.-Z., Edwards, M. J., Rounis, E., Bhatia, K. P., & Rothwell, J. C. (2005). Theta Burst Stimulation of the Human Motor Cortex. *Neuron*, *45*(2), 201–206. https://doi.org/10.1016/j.neuron.2004.12.033

Hurks, P. P. M., Vles, J. S. H., Hendriksen, J. G. M., Kalff, A. C., Feron, F. J. M., Kroes, M., … Jolles, J. (2006). Semantic Category Fluency Versus Initial Letter Fluency Over 60 Seconds as a Measure of Automatic and Controlled Processing in Healthy School-aged Children. *Journal of Clinical and Experimental Neuropsychology*, *28*(5), 684–695. https://doi.org/10.1080/13803390590954191

Ihara, A. S., Mimura, T., Soshi, T., Yorifuji, S., Hirata, M., Goto, T., … Fujimaki, N. (2015). Facilitated Lexical Ambiguity Processing by Transcranial Direct Current Stimulation over the Left Inferior Frontal Cortex. *Journal of Cognitive Neuroscience*, *27*(1), 26–34. https://doi.org/10.1162/jocn_a_00703

Indefrey, P., & Cutler, A. (2004). Prelexical and lexical processing in listening. In M. Gazzaniga (Ed.),*The cognitive neurosciences III.*(pp. 759-774).Cambridge,MA: MIT Press.

Jacobson, S. (2017). *Neuroanatomy for the neuroscientist*. New York, NY: Springer Science+Business Media.

Jefferies, E., Patterson, K., Jones, R. W., & Lambon Ralph, M. A. (2009). Comprehension of concrete and abstract words in semantic dementia. *Neuropsychology*, *23*(4), 492–499. https://doi.org/10.1037/a0015452

Joyal, M., & Fecteau, S. (2016). Transcranial Direct Current Stimulation Effects on Semantic Processing in Healthy Individuals. *Brain Stimulation*, *9*(5), 682–691. https://doi.org/10.1016/j.brs.2016.05.003

Koechlin, E. (2014). An evolutionary computational theory of prefrontal executive function in decision-making. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1655), 20130474–20130474. https://doi.org/10.1098/rstb.2013.0474

Kahneman, D. (2011). *Thinking, fast and slow.* New York: Farrar, Straus and Giroux

Liu, A., Vöröslakos, M., Kronberg, G., Henin, S., Krause, M. R., Huang, Y., … Buzsáki, G. (2018). Immediate neurophysiological effects of transcranial electrical stimulation. *Nature Communications*, *9*(1). https://doi.org/10.1038/s41467-018-07233-7

Luke, S. G. (2017). Evaluating significance in linear mixed-effects models in R. *Behavior Research Methods*, *49*(4), 1494–1502. https://doi.org/10.3758/s13428-016-0809-y

Marko, M., Michalko, D., & Riečanský, I. (2018a). Remote associates test: An empirical proof of concept. *Behavior Research Methods*. https://doi.org/10.3758/s13428-018-1131-7

Marko, M., Michalko, D., & Riecansky, I. (2018b). *The effects of prefrontal transcranial direct-current stimulation on semantic control functions*.

McClelland, J. L., & Rogers, T. T. (2003). The parallel distributed processing approach to semantic cognition. *Nature Reviews Neuroscience*, *4*(4), 310–322. https://doi.org/10.1038/nrn1076

Medin, D. L., & Schaffer, M. M. (1978). Context theory of classification learning. *Psychological Review*, *85*(3), 207-238. http://dx.doi.org/10.1037/0033-295X.85.3.207

Mirman, D., & Britt, A. E. (2013). What we talk about when we talk about access deficits. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1634), 20120388–20120388. https://doi.org/10.1098/rstb.2012.0388

Mirman, D., Landrigan, J.-F., & Britt, A. E. (2017). Taxonomic and thematic semantic systems. *Psychological Bulletin*, *143*(5), 499–520. https://doi.org/10.1037/bul0000092

Miyake, A., Friedman, N. P., Emerson, M. J., Witzki, A. H., Howerter, A., & Wager, T. D. (2000). The Unity and Diversity of Executive Functions and Their Contributions to Complex "Frontal Lobe" Tasks: A Latent Variable Analysis. *Cognitive Psychology*, *41*(1), 49–100. https://doi.org/10.1006/cogp.1999.0734

Monti, A., Ferrucci, R., Fumagalli, M., Mameli, F., Cogiamanian, F., Ardolino, G., & Priori, A. (2013). Transcranial direct current stimulation (tDCS) and language. *Journal of Neurology, Neurosurgery & Psychiatry*, *84*(8), 832–842. https://doi.org/10.1136/jnnp-2012-302825

Nitsche, M. A., Fricke, K., Henschke, U., Schlitterlau, A., Liebetanz, D., Lang, N., … Paulus, W. (2003). Pharmacological Modulation of Cortical Excitability Shifts Induced by Transcranial Direct Current Stimulation in Humans. *The Journal of Physiology*, *553*(1), 293–301. https://doi.org/10.1113/jphysiol.2003.049916

Nitsche, M. A., & Paulus, W. (2000). Excitability changes induced in the human motor cortex by weak transcranial direct current stimulation. *The Journal of Physiology*, *527*(3), 633–639. https://doi.org/10.1111/j.1469-7793.2000.t01-1-00633.x

Nitsche, M. A., Seeber, A., Frommann, K., Klein, C. C., Rochford, C., Nitsche, M. S., … Tergau, F. (2005). Modulating parameters of excitability during and after transcranial direct current stimulation of the human motor cortex: Cortical excitability and tDCS. *The Journal of Physiology*, *568*(1), 291–303. https://doi.org/10.1113/jphysiol.2005.092429

O'Kane, G., Kensinger, E. A., & Corkin, S. (2004). Evidence for semantic learning in profound amnesia: An investigation with patient H.M. *Hippocampus*, *14*(4), 417–425. https://doi.org/10.1002/hipo.20005

Ozen, S., Sirota, A., Belluscio, M. A., Anastassiou, C. A., Stark, E., Koch, C., & Buzsaki, G. (2010). Transcranial Electric Stimulation Entrains Cortical Neuronal Populations in Rats. *Journal of Neuroscience*, *30*(34), 11476–11485. https://doi.org/10.1523/JNEUROSCI.5252-09.2010

Patterson, K., Nestor, P. J., & Rogers, T. T. (2007). Where do you know what you know? The representation of semantic knowledge in the human brain. *Nature Reviews Neuroscience*, *8*(12), 976–987. https://doi.org/10.1038/nrn2277

Paulus, W. (2011). Transcranial electrical stimulation (tES – tDCS; tRNS, tACS) methods. *Neuropsychological Rehabilitation*, *21*(5), 602–617. https://doi.org/10.1080/09602011.2011.557292

Poitrenaud, S., Richard, J.-F., & Tijus, C. (2005). Properties, categories, and categorisation. *Thinking & Reasoning*, *11*(2), 151–208. https://doi.org/10.1080/13546780442000169

Pisoni, A., Mattavelli, G., Papagno, C., Rosanova, M., Casali, A. G., & Romero Lauro, L. J. (2018). Cognitive Enhancement Induced by Anodal tDCS Drives Circuit-Specific Cortical Plasticity. *Cerebral Cortex*, *28*(4), 1132–1140. https://doi.org/10.1093/cercor/bhx021

Posner, M. I., & Snyder, C. R. R. (2004). Attention and Cognitive Control. In D. A. Balota & E. J. Marsh (Eds.), *Key readings in cognition. Cognitive psychology: Key readings* (pp. 205-223). New York, NY, US: Psychology Press.

Ralph, M. A. L., Jefferies, E., Patterson, K., & Rogers, T. T. (2017). The neural and computational bases of semantic cognition. *Nature Reviews Neuroscience, 18*(1), 42–55. https://doi.org/10.1038/nrn.2016.150

Reti, I. (2015). *Brain Stimulation*. Hoboken, New Jersey: John Wiley & Sons.

Robbins, T. W. (1990). The prefrontal cortex, 2nd edn. J. M. Fuster. Raven Press, New York, 1989. Price:$86.50. *International Journal of Geriatric Psychiatry*, *5*(5), 348–348. https://doi.org/10.1002/gps.930050518

Rosch, E. (2002). Principles of categorization. In D. J. Levitin (Ed.), *Foundations of cognitive psychology: Core readings* (pp. 251-270). Cambridge, MA, US: MIT Press.

Rowe, J. B., & Frackowiak, R.S. (2003). Neuroimaging. In L. Nadel(Ed.), Encyclopedia of cognitive science (Vol. 1, pp. 2270–2279).London: Nature Publishing Group.

Semendeferi, K., Armstrong, E., Schleicher, A., Zilles, K., & Van Hoesen, G. W. (2001). Prefrontal cortex in humans and apes: A comparative study of area 10. *American Journal of Physical Anthropology*, *114*(3), 224–241. https://doi.org/10.1002/1096-8644(200103)114:3<224::AID-AJPA1022>3.0.CO;2-I

Masson, M. E. J. (2001). Priming, Cognitive Psychology. In Smelser, N. J., & Baltes, P. B. (Eds.). (2001). *International encyclopedia of the social & behavioral sciences* (1st ed). Amsterdam ; New York: Elsevier.

Smith, L. B. (2005). Cognition as a dynamic system: Principles from embodiment. *Developmental Review*, *25*(3–4), 278–298. https://doi.org/10.1016/j.dr.2005.11.001

Splitberger, R. (2018) *Snell´s clinical neuroanatomy.* Philadelphia : Wolters Kluwer

Squire, L. R., & Zola, S. M. (1998). Episodic memory, semantic memory, and amnesia. *Hippocampus*, *8*(3), 205-211. http://dx.doi.org/10.1002/(SICI)1098-1063(1998)8:3<205::AID-HIPO3>3.0.CO;2-I

Sternberg, R. J., & Sternberg, K. (2011). *Cognitive Psychology*. Belmont. Callifornia: Wadsworth Publishing.

Terney, D., Chaieb, L., Moliadze, V., Antal, A., & Paulus, W. (2008). Increasing Human Brain Excitability by Transcranial High-Frequency Random Noise Stimulation. *Journal of Neuroscience*, *28*(52), 14147–14155. https://doi.org/10.1523/JNEUROSCI.4248-08.2008

Tulving, E. (1972). Episodic and semantic memory. In E. Tulving & W. Donaldson, *Organization of memory.* Oxford, England: Academic Press.

Uylings, H. B. M., Groenewegen, H. J., & Kolb, B. (2003). Do rats have a prefrontal cortex? *Behavioural Brain Research*, *146*(1–2), 3–17. https://doi.org/10.1016/j.bbr.2003.09.028

Vöröslakos, M., Takeuchi, Y., Brinyiczki, K., Zombori, T., Oliva, A., Fernández-Ruiz, A., … Berényi, A. (2018). Direct effects of transcranial electric stimulation on brain circuits in rats and humans. *Nature Communications, 9*(1). https://doi.org/10.1038/s41467-018-02928-3

Wagner, A. D., Maril, A., Bjork, R. A., & Schacter, D. L. (2001). Prefrontal Contributions to Executive Control: fMRI Evidence for Functional Distinctions within Lateral Prefrontal Cortex. *NeuroImage*, *14*(6), 1337–1347. https://doi.org/10.1006/nimg.2001.0936

Westbrook, A., & Braver, T. S. (2015). Cognitive effort: A neuroeconomic approach. *Cognitive, Affective, & Behavioral Neuroscience*, *15*(2), 395–415. https://doi.org/10.3758/s13415-015-0334-y

Whitney, C., Grossman, M., & Kircher, T. T. J. (2009). The Influence of Multiple Primes on Bottom-Up and Top-Down Regulation during Meaning Retrieval: Evidence for 2 Distinct Neural Networks. *Cerebral Cortex*, *19*(11), 2548–2560. https://doi.org/10.1093/cercor/bhp007

Whitney, C., Kirk, M., O'Sullivan, J., Lambon Ralph, M. A., & Jefferies, E. (2011). The Neural Organization of Semantic Control: TMS Evidence for a Distributed Network in Left Inferior Frontal and Posterior Middle Temporal Gyrus. *Cerebral Cortex*, *21*(5), 1066–1075. https://doi.org/10.1093/cercor/bhq180

Wittgenstein, L. (1968). *Philosophical investigations*. Oxford: Basil Blackwell.

Wixted J.T. & Thompson-Schill S. L (2018). *Stevens' Handbook of Experimental Psychology and Cognitive Neuroscience, Language and Thought (Volume 3) Volume 3 Edition*. New York: Wiley publishing

Woods, D. L., Wyma, J. M., Yund, E. W., Herron, T. J., & Reed, B. (2015). Factors influencing the latency of simple reaction time. *Frontiers in Human Neuroscience*, *9*. https://doi.org/10.3389/fnhum.2015.00131

Attachements

Figure 1. (Aboitz, 2017)

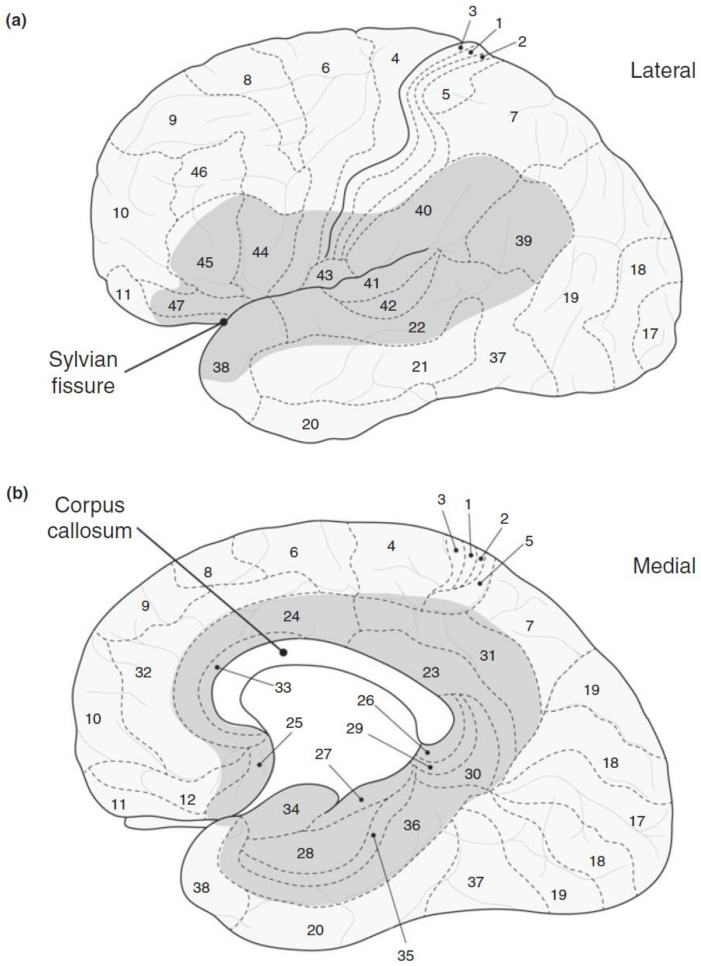


Fig. 2.2 Lateral and medial aspects of the human cerebral hemispheres. Figures depict Brodmann's cortical areas in numbers, and the longitudinal subdivisions specified by Foville in gray. (**a**) In the lateral aspect, Foville's *circonvolution d'enceinte*, or the Sylvian convolution surrounds the Sylvian fissure. This includes the inferior parietal lobe (areas 39 and 40, angular and supramarginal gyri), the ventrolateral prefrontal cortex (areas 44-pars opercularis, 45-pars triangularis, and 47), and the ventral premotor (area 6), motor (area 4), somatosensory (areas 3, 1, 2) and insular (area 43) regions. In the temporal lobe, areas 22, 41 and 42 make up the superior temporal gyrus, which is separated from the middle and inferior temporal gyri (areas 20, 21 and 37) by the superior temporal sulcus (not shown). The temporal pole corresponds to area 38. (**b**) The medial aspect of the hemisphere depicts Foville's and Broca's limbic lobe (in gray). The anterior cingulate cortex corresponds to area 24, and areas 23, 26, 29, 30 and 31 behind the corpus callosum make up the posterior cingulate cortex or retrosplenial region. The default mode network involves areas 10 and 32 in the frontal lobe, and the posterior cingulate cortex

Figure 2. (Hagoort, 2005)

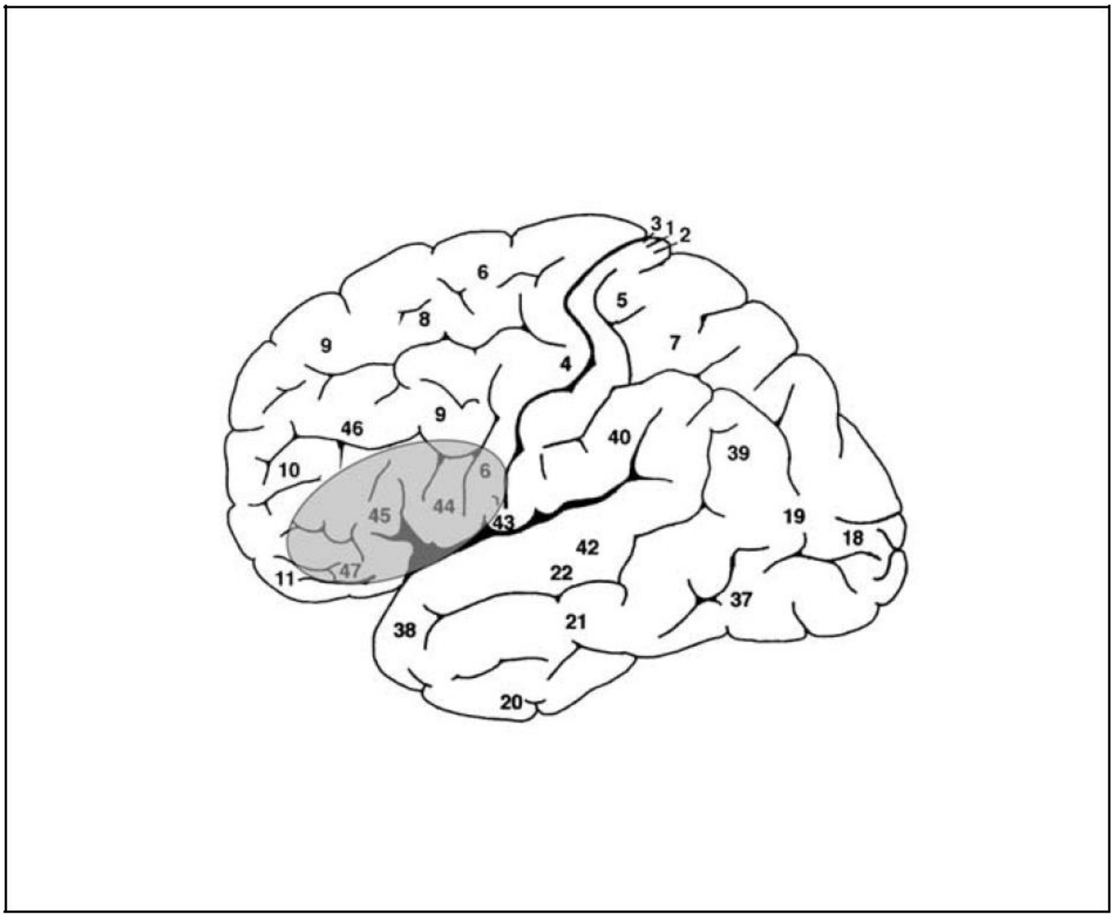


Figure 3. (Aboitz, 2017)

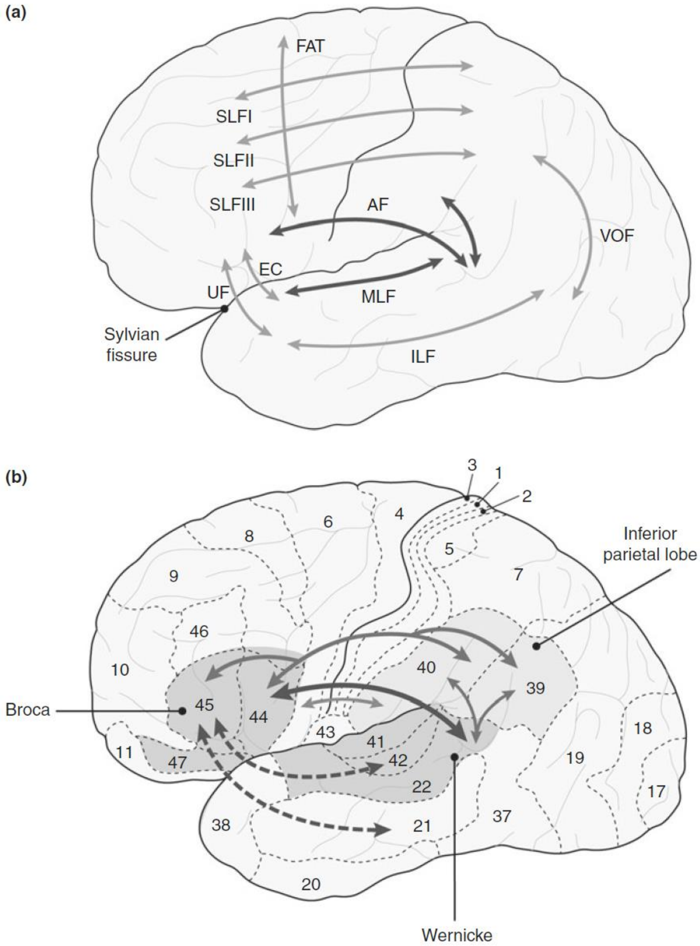


Fig. 2.3 The main cortico-cortical tracts discussed in this book. (**a**) This schematic is not intended to be anatomically accurate but to reflect the topographical arrangement of these tracts. In addition, these tracts are not discrete bundles but rather overlap in a continuous plexus below the cortical surface. AF, Arcuate fasciculus; EC, Extreme capsule; FAT, Frontal aslant tract; ILF, Inferior longitudinal fasciculus; MLF, middle longitudinal fasciculus; SLF I, II, III, dorsal, middle and ventral components of the superior longitudinal fasciculus, respectively; UF, Uncinate fasciculus; VOF, Vertical occipital fasciculus. The curved arrow at the posterior end of the Sylvian fissure connects superior temporal and inferior parietal areas, and has been termed the posterior segment of either the arcuate fasciculus or the middle longitudinal fasciculus, depending on the nomenclature. (**b**) Functional subdivisions and connectivity of the language-related circuit. In the superior temporal gyrus, areas 41 and 42 make up the auditory cortex, while Wernicke's area roughly corresponds to posterior area 22. Broca's area, in a restricted sense, has been defined as area 44-pars opercularis, and area 45-pars triangularis. The dorsal language pathway has two components, one connecting Wernicke's area mainly with area 44 and neighboring regions via the arcuate fasciculus (black arrow), and the other connecting Wernicke's area with the inferior parietal lobe, and then projecting to areas 44 and 45 via the superior longitudinal fasciculus (dark gray arrows). There are additional connections between motor, premotor and somatosensory areas (light gray arrow). The ventral pathway (segmented arrows) is a polysynaptic tract that connects the anterior temporal gyrus (auditory component), and the middle and inferior temporal gyri (visual component) with areas 45 and 47

Figure 4. (Hagoort, 2005)

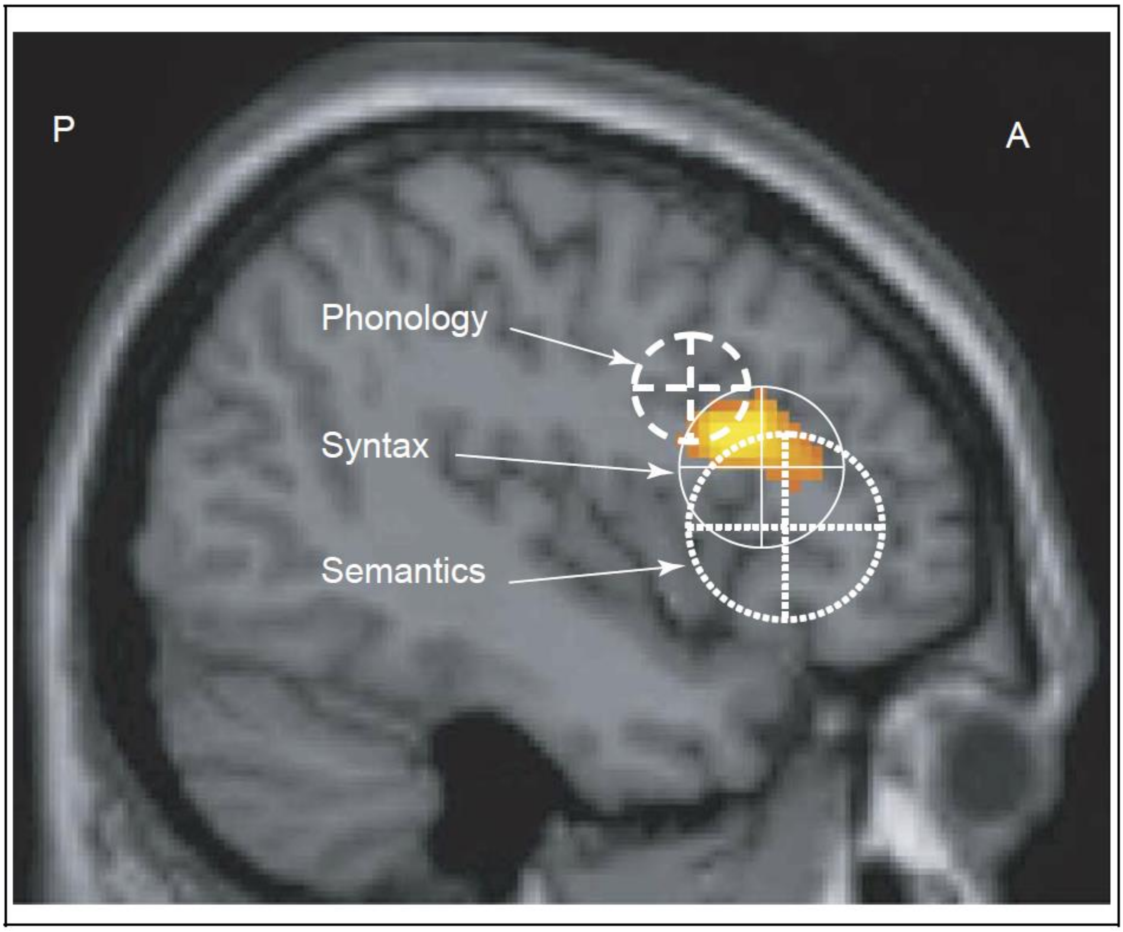


Figure 5.

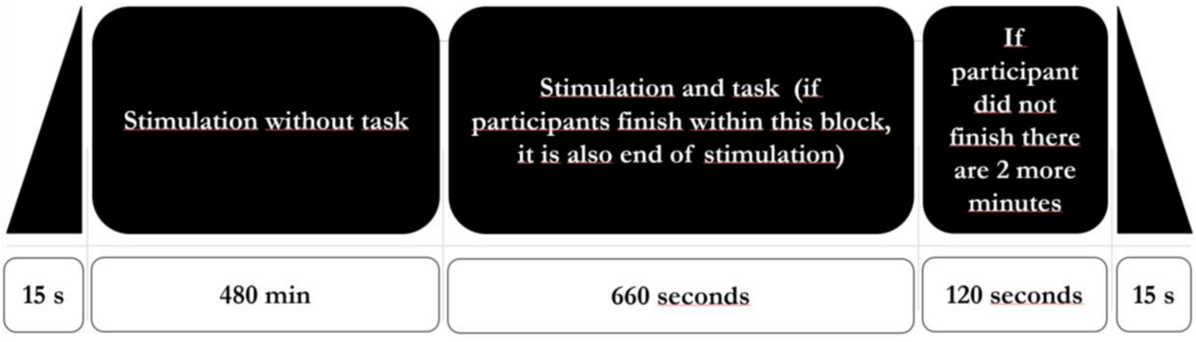
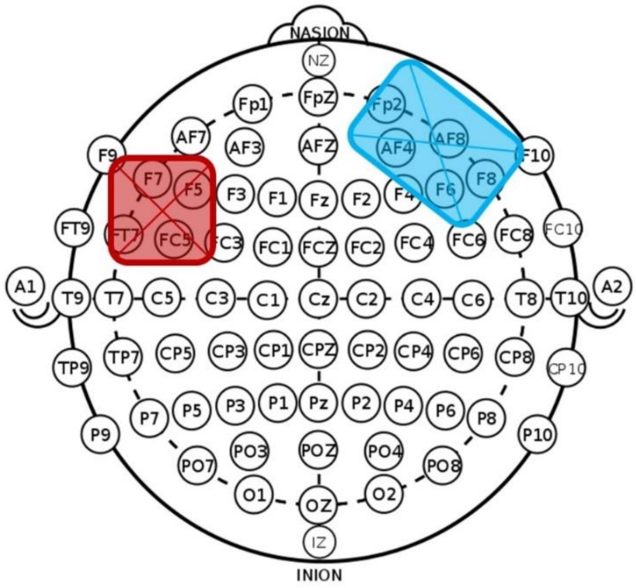

Stimulation without task
Stimulation and task (if participants finish within this block, it is also end of stimulation)
If participant did not finish there are 2 more minutes
15 s
480 min
660 seconds
120 seconds
15 s

Figure 6.


NASION
NZ
Fp1
FpZ
Fp2
AF7
AF3
AFZ
AF4
AF8
F9
F7
F5
F3
F1
Fz
F2
F4
F6
F8
F10
FT9
FT7
FC5
FC3
FC1
FCZ
FC2
FC4
FC6
FC8
FC10
A1
T9
T7
C5
C3
C1
Cz
C2
C4
C6
T8
T10
A2
TP9
TP7
CP5
CP3
CP1
CPZ
CP2
CP4
CP6
CP8
CP10
P9
P7
P5
P3
P1
Pz
P2
P4
P6
P8
P10
PO7
PO3
POZ
PO4
PO8
O1
OZ
O2
IZ
INION