Univerzita Komenského v Bratislave
Fakulta matematiky, fyziky a informatiky

The role of sensorimotor grounding of concepts in semantic memory retrieval

Diploma Thesis

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Diploma Thesis

Study program:	Cognitive Science
Field of Study:	Computer Science
Department:	Department of Applied Informatics
Supervisor:	Mgr. Martin Marko, PhD

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Názov: The role of sensorimotor grounding of concepts in semantic memory retrieval
Úloha senzomotorického ukotvenia pojmov pri vybavovaní zo sémantickej pamäti

Anotácia: Sémantická pamäť kóduje, organizuje a ukladá vedomosti. Rôzne kognitívne procesy si vyžadujú rýchle a presné vybavovanie zo sémantickej pamäti. Pomocou transkraniálnej elektrickej stimulácie ľavej prefrontálnej kôry (PFC) a hodnotenia senzomotorických dimenzií stimulov možno skúmať, či stupeň senzomotorického ukotvenia slov predikuje výkon účastníkov pri úlohách zameraných na sémantickú pamäť. Práca má potenciál poskytnúť vzhľad do funkčného zapojenia ľavého PFC pri sémantickom spracovaní a vybavovania z pamäti a v rámci paradigmy ukotvenej kognície.

Cieľ: Preskúmať úlohu ľavej prefrontálnej kôry (PFC) pri automatickom a riadenom vybavovaní zo sémantickej pamäti z pohľadu teórie ukotvenej kognície. Súčasťou práce je aj zber senzomotorických hodnotení slovenských slov, kvôli určeniu ich vplyvu na vybavovanie zo sémantickej pamäti účastníkov.

Literatúra:
Marko, M., & Riečanský, I. (2021). The left prefrontal cortex supports inhibitory processing during semantic memory retrieval. Cortex, 134, 296–306. https://doi.org/https://doi.org/10.1016/j.cortex.2020.11.001
Fernandino, L. et al. (2016). Heteromodal cortical areas encode sensory-motor features of word meaning. Journal of Neuroscience, 36 (38), 9763–9769. https://doi.org/10.1523/JNEUROSCI.4095-15.2016
Kemmerer, D. (2014). Cognitive neuroscience of language (1st ed.). Psychology Press.

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Title: The role of sensorimotor grounding of concepts in semantic memory retrieval

Annotation: Semantic memory encodes, organizes, and stores knowledge. Different cognitive capacities require rapid and accurate retrieval from semantic memory. Using the transcranial direct-current stimulation of the left prefrontal cortex (PFC) and assessing sensorimotor dimensions of stimulus words, investigate whether the degree of sensorimotor grounding of stimulus words predicts participants' performance on semantic memory tasks. The thesis has a potential to provide insights into the functional role of the left PFC in semantic processing and memory retrieval within the grounded cognition paradigm.

Aim: Investigate the role of the left prefrontal cortex (PFC) during automatic and controlled semantic memory retrieval from the perspective of grounded cognition theory. Additionally, collect sensorimotor ratings of Slovak words to determine their impact on participants' semantic memory retrieval.

Literature: Marko, M., & Riečanský, I. (2021). The left prefrontal cortex supports inhibitory processing during semantic memory retrieval. Cortex, 134, 296–306. https://doi.org/https://doi.org/10.1016/j.cortex.2020.11.001
Fernandino, L. et al. (2016). Heteromodal cortical areas encode sensory-motor features of word meaning. Journal of Neuroscience, 36 (38), 9763–9769. https://doi.org/10.1523/JNEUROSCI.4095-15.2016
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Declaration: I hereby declare that the entire diploma thesis: "The role of sensorimotor grounding of concepts in semantic memory retrieval", along with attachments and illustrations was created independently by the author, using the literature listed in the attached list and artificial intelligence tools. Specifically, Google Gemini was used to generate supporting materials from recherche and notes created by the author. I declare that artificial intelligence tools have been used following the relevant legislation, academic rights and freedoms, and ethical and moral principles, along with respecting academic integrity, and that their use is appropriately indicated in the thesis.

Acknowledgment: First and foremost, I'd like to thank my supervisor, Martin Marko for his in-depth knowledge of the topic, patience, and ongoing support throughout the whole process of creating this thesis. Additionally, I'd like to express my gratitude to Adam Kubinec and Rastislav Rovný for guidance during the data collection phase. Finally, I would like to thank Andrea Valentová and Barbora Michalkova, who contributed to the data collection phase, despite not sharing the same focus of study and research questions. Finally, this thesis was created thanks to the following grants: 1. APVV, no. APVV-19-0570, title: "Cognitive and brain mechanisms of semantic processing" (principal investigator: Igor Riečanský) and 2. VEGA, no. 2/0052/23, title: "Neurocognitive mechanisms of semantic representation and control" (principal investigator: Martin Marko).

Abstrakt

V tejto práci sme skúmali úlohu ľavej prefrontálnej kôry (PFC) pri riadenom a automatickom semantickom spracovaní z pohľadu ukotvenej kognície.

Najprv sme formou online dotazníka uskutočnili prieskum, v ktorom sme zisťovali senzomotorické vlastnosti slov v slovenskom jazyku. Následne sme získané údaje aplikovali na posúdenie úlohy senzomotorických atribútov pri sémantickom spracovaní. Uskutočnili sme experiment, v rámci ktorého zdraví účastníci absolvovali úlohu zameranú na asociatívne a disociatívne vyhľadávanie v sémantickej pamäti (ADT). Úlohy ADT sú navrhnuté tak, aby sa zapojilo automatické, resp. kontrolované vyhľadávanie. Okrem toho sme skúmali úlohu prefrontálnej kôry (PFC) pomocou transkraniálnej stimulácie tDCS, aplikovanej na oblasť ventrolaterálneho PFC.

Výsledky tejto štúdie sú v súlade s modelom ukotvenej kognície, čo naznačuje, že senzomotorické atribúty slov zohrávajú úlohu počas sémantického vybavovania. Zaujímavé je, že výsledky naznačujú, že konkrétne slová sa ľahšie vybavujú z pamäti počas automatického, ale už nie počas kontrolovaného vyhľadávania. Nepodarilo sa nám zreprodukovať predchádzajúce štúdie naznačujúce, že anodálna stimulácia ľavej PFC zlepšuje kontrolované sémantické vyhľadávanie. Avšak podarilo sa nám potvrdiť, že ľavá PFC je kauzálne zapojená do kontrolovaného semántického vyhľadávania, čím sme priniesli ďalšiu podporu modelu riadeného sémantického poznania (CSC).

V neposlednom rade, táto štúdia poskytuje nový pohľad na funkčnú úlohu ľavého PFC. Vypozorovali sme, že stimulácia ľavého ventrolaterálneho PFC interferuje s kontrolovaným sémantickým vyhľadávaním, čo prináša ďalšiu podporu CSC modelu. Avšak na rozdiel od predchádzajúcich štúdií sme nezaznamenali výraznu rolu ľavého PFC počas spracovania abstraktnejších slov. A preto je potrebný ďalší výskum na získanie hlbšieho vzhľadu do tejto problematiky.

Kľúčové slová: ukotvená kognícia, tDCS, riadená sémantická kontrola

Abstract

In the present thesis, we have examined the role of the left prefrontal cortex (PFC) in controlled and automatic semantic processing from the Grounded Cognition perspective.

First, we conducted a survey, in the form of an online questionnaire, gathering the sensorimotor features of the words in the Slovak language. Afterward, we applied the resulting data to assess the role of sensorimotor features in semantic processing. An experimental study was carried out, wherein healthy participants underwent the associative-dissociative retrieval task (ADT). The ADT tasks consist of associative and dissociative retrieval tasks, designed to engage the automatic and controlled retrieval, respectively. Moreover, we examined the role of the prefrontal cortex (PFC) by transcranial direct-current stimulation tDCS applied to the ventrolateral PFC.

The outcomes of this study align with the Grounded Cognition Model, suggesting that sensorimotor features play a role during semantic processing. Interestingly, the results suggest that concrete words are more easily retrieved from memory during automatic, but not during controlled semantic retrieval. We were unable to replicate previous studies suggesting that anodal stimulation of the left PFC improves controlled semantic retrieval. However, we were able to confirm that the left PFC is causally involved in controlled semantic retrieval, providing further support for the controlled semantic cognition (CSC) model.

Finally, this study provides a novel insight into the functional role of left PFC. We observed that stimulation of the left ventrolateral PFC enhances controlled semantic retrieval bringing further support to the Controlled Semantic Cognition model. Contrary to previous studies, we did not observe a more pronounced role of the left PFC during the processing of more abstract words. Therefore, additional research is needed to gain deeper insight into the problem.

Keywords: grounded cognition, tDCS, controlled semantic cognition

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Chapter 1

Semantic Cognition

Semantic cognition encompasses the mental processes associated with comprehending and employing meaning in language and thought. One of the key problems in the study of semantic cognition is the formation and manipulation of concepts. As noted by Kiefer and Pulvermüller (2012), the discourse on the nature of concepts predates the establishment of psychology as an experimental science. During the Enlightenment rationalists like Descartes, Spinoza, and Leibniz asserted reason as the only path to knowledge and emphasized *A Priori* knowledge independent of past sensory experiences. This concept has roots back in Ancient Greece, with Plato proposing the existence of *Forms*—static and eternal entities, that could be understood only through reason. In contrast, Epicureans held a materialistic view, prioritizing sensations and feelings as the criteria for studying the world. Empiricists revived these philosophical ideas during the Enlightenment to contrast theories of rationalists (Kemmerer, 2014; Kiefer & Pulvermüller, 2012).

The initial half of the 20th century witnessed the dominance of behaviorism in psychology (e.g., Pavlov, 1928; Watson, 1913). Behaviorism emerged as a response to early psychology's introspective and consciousness-centric methods, thus rejecting the exploration of subjective mental processes in favor of studying directly observable behaviors. Behaviorists focused attention on the role of stimuli and responses in shaping behavior. This viewpoint extended to the study of language as well. Skinner (1957) articulated a viewpoint on language acquisition, proposing that language, is acquired through *operant conditioning*. According to this perspective, individuals learn the meaning of words through their experiences and the consequences of using those words. Therefore the meanings of words are shaped by the context in which they are employed. Thus, semantic cognition consists of a process of a gradual approximation of desired behavior and its subsequent reinforcement. Behaviorism's exclusive focus on observable behavior led to its significant criticism, as its reductionism of cognitive, emotional, and social factors to stimulus-response association struggled to explain key aspects of semantic cognition.

Influenced by advancements in mathematical logic and computer science during the early 20th century (including Gödel, 1931a, 1931b; Turing, 1936), Chomsky (1959) conducted a critique of Skinner's theory. A few years before that, Chomsky developed a theory of transformational grammars (Chomsky, 1955). According to this viewpoint, grammar is a set of rules meant to transform the combinations of words into grammatically correct sentences within a specific language. The new sentences are created by modifying existing sentences with operations known as *transformations*. Furthermore, Chomsky introduced the concept of *innate grammar*, proposing that humans possess a biological predisposition to language acquisition. The rejection of measurable behavior as the sole source of evidence allowed for the birth of cognitive psychology. This shift facilitated the emergence of multiple theories, notably with Tulving (1972) introducing the dual-process model of long-term memory. In the paper, he proposed the distinction between episodic and semantic memory. Semantic memory operates by storing information in a decontextualized manner. It serves as a storage of general knowledge, consisting of facts, meanings, and concepts stored independently of specific times, places, or personal experiences. In contrast, episodic memory is dedicated to preserving experiences and events along with the context in which they occurred. Tulving's dual-process model has provided an important framework for understanding how different types of information are processed and stored in long-term memory.

Furthermore, Chomsky's work significantly influenced the emergence of the Amodal Symbolic Model (e.g., Collins & Loftus, 1975; Fodor, 1975; Quillian, 1967; Smith et al., 1974), which dominated conceptual knowledge theory from the 1970s to the 1990s. This model assumes that concepts consist solely of abstract symbols encoded and processed in an autonomous semantic system independent of modality-specific systems (Kemmerer, 2014). For example, the concept represented by the word 'dog' might be encoded by purely abstract symbols in the form of a list [fur, stink, bark, saliva]. Therefore, the understanding of the word does not require access to memories associated with our perceptions and feelings associated with dogs. In the 1980s, theories collectively known as the Grounded Cognition Model (GCM; Barsalou, 2008) emerged in response to the Amodal Symbolic Model. The central idea of this model is that semantic knowledge is linked to the sensations experienced during interactions with the world and sensorimotor experiences guide the structure and meaning of concepts. Therefore, semantic processing requires the initiation of sensorimotor data from a long-term memory that contains information about the ways we interact with the objects and about our sensual experiences with them (Kemmerer, 2014).

The study of semantic cognition has undergone a dynamic evolution, from early years of behaviorism to cognitive psychology, and now to competing models of conceptual knowledge. Despite decades of research in semantic cognition, the nature of concepts along with the means of their acquisition, and the role of past sensory experience in shaping conceptual processing remain an open question. In the next chapter, we will look further into the ongoing debate between the Amodal Symbolic Model and the Grounded Cognition Model, to further contribute to the understanding of semantic cognition.

Chapter 2

Classical vs. Grounded Cognition

2.1. Classical Views

As discussed in the preceding chapter, psychologists in the 1960s and 1970s, inspired by rapid advancements in computer science, formulated several theories to explain the organization and representation of semantic information. A key feature shared by these models was the *amodality* of concepts (Kemmerer, 2014).

One early theoretical framework: A Spreading-Activation Theory of Semantic Processing employed a semantic network to simulate human semantic processing with a digital computer (Quillian, 1967). This model presumed an organized structure of information, resembling a hierarchical tree. Nodes at the top were general or *superordinate* concepts, while nodes further down the network contained more specific or *subordinate* concepts. Links represented relationships between concepts, stored as various types of labeled pointers. For instance, the statement: 'A dog is a mammal' implies that 'dog' is subordinate to 'mammal' in the hierarchy. Additionally, the model assumed the inheritance of properties from superordinate concepts by subordinate concepts (e.g., if 'mammals are warm-blooded', then 'dogs are warm-blooded' as well). Furthermore, the model incorporated the theory of *spreading activation*, assuming iterative propagation of activation caused by one concept through interconnected links to related concepts. Thus reflecting the idea, that contemplation and information retrieval of one concept can cause spontaneous retrieval of information about related concepts (Collins & Loftus, 1975).

Smith et al. (1974) extended this theory, giving rise to the Semantic Feature Model. In this model, concepts are represented by a set of semantic features, that capture distinctive features associated with each concept. These concepts are hierarchically organized based on these attributes with the model introducing a distinction between *defining* features and *characteristic* features. The defining features are essential for the meaning of a concept, while the characteristics are associated with, but not necessary for the definition of the concept. Furthermore, the model claims, that the concepts vary between the levels of possession of the given features, with certain features being more prominent than others. Moreover, the model is in line with the idea of *family resemblance*, suggesting that concepts do not need to share all of the defining features, but rather belong to the same category by sharing multiple characteristic features.

Theories of amodal symbols have faced criticism on various fronts. Their incorporation into cognitive psychology during its formative years offered a sophisticated formal means of semantic memory representation. Nevertheless, they were concurrently challenged for lacking empirical support and biological plausibility (Barsalou, 2008). In particular, amodal models of cognition encountered difficulties in pinpointing the storage location of purely abstract symbols and maintaining alignment with neural computational principles. Additionally, these traditional theories struggled to propose viable solutions to the *grounding problem* (Barsalou, 2008), the problem of how concepts (symbols) get their meanings (Harnad, 1990).

2.2. Embodied Views

In response to mounting criticisms directed at the Amodal Symbolic Model, multiple theories collectively known as Grounded Cognition Models (GCM) emerged. As illustrated on **Figure 3.1**, the central idea posits that conceptual knowledge is *not* completely detached from perception and action. Instead, these models propose an overlap between semantic knowledge and perception-action (Barsalou, 1999, 2009; Kemmerer, 2014; Shapiro, 2019). For example, the Theory of Perceptual Symbol Systems proposes that perceptual experiences involve the capture of sensory-motor patterns in the brain's association areas (Barsalou, 1999). Furthermore, Barsalou (2009) proposed, that the re-enactment process plays a crucial component in semantic memory retrieval. He posited the existence of *simulators* which integrate multimodal information from an experience and can later reactivate the perceptual state, to produce simulations of concepts and make predictions about actions likely to be effective while interacting with them.

Some of the earliest evidence in favor of grounded cognition emerged from the study of linguistics. Lakoff and Johnson (1980) proposed, that metaphors are not constrained to poetic language. On the contrary, our whole conceptual system is fundamentally metaphorical in nature. They suggest that individuals draw knowledge from bodily experiences through interoception and that abstract concepts stem metaphorically from this process. For instance, the phrase 'frozen by fear' symbolizes the metaphorical link between the

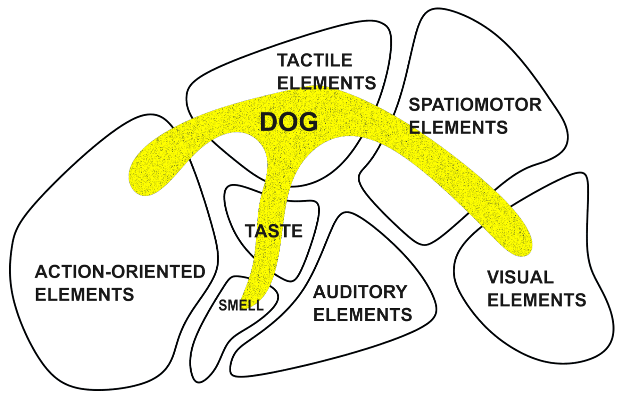

Figure 2.1: According to GCM, concepts are stored in distinct modality-specific systems (based on illustration from Kemmerer, 2014)

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physical sensation of freezing and the abstract emotion of fear. Further linguistic evidence comes from the compatibility of GCM with observed cross-lingual differences, which have been largely neglected by amodal theories. For example, languages differ to some extent in the ways they refer to body parts, with some languages lacking a general term for 'face' or 'leg', and some even lacking a general term meaning 'body'. Instead, they contain multiple finer discriminatory terms, such as 'upper leg", 'lower lip' or 'eyelid' (Enfield et al., 2006). Furthermore, despite the majority of humans having trichromatic vision, languages vary in the number of basic color words, which may be associated with a relative usefulness of vocabulary expansion for the given culture (Conway et al., 2016). As articulated by Kemmerer (2022), this observed linguistic relativity must be taken into account by GCM. Therefore, concepts are not only rooted in modality-specific representations, but these representations are necessarily language-specific.

Furthermore, three sources of psychological and neurological evidence supporting the embodied concept were identified by Shapiro (2019). Firstly, numerous experimental studies have demonstrated that introducing a perceptual stimulus or manipulating perceptual attributes in the environment influences access to perceptual knowledge, while the knowledge in different perceptual systems or encyclopedic knowledge remains unaffected (Amsel et al., 2014; Edmiston & Lupyan, 2017). The second line of evidence for embodied concepts comes from the observation of the role of imagery during a variety of tasks, where one group is asked to approach the problem with the construction of mental images to answer the questions involved in the task, while the other is not given any explicit guidance.

Modal theory of concepts predicts similar performance on tasks because it inherently assumes that thought is modal by default. In contrast, amodal theories do not make this prediction. Indeed, results on a variety of tasks reveal that the neutral group's task performance matches that of the imagery group (Wu & Barsalou, 2009). Lastly, abundant neuroimaging evidence, which will be discussed in the next chapter, lends support to the proposition that the neural substrates underlying semantic processes are distributed extensively across significant portions of the brain (Binder et al., 2009). Neurophysiological findings further indicate that concepts exhibit functional and neuroanatomical connections with sensory brain regions, thereby endorsing the notion of concepts grounded in sensorimotor sensations (Kiefer & Pulvermüller, 2012). In one notable study, Fernandino et al. (2015) created a multivariant fMRI design experiment. First, they developed a set of sensorimotor ratings of concepts in the English language. Ratings of the relevance of the 5 attributes (sound, color, manipulation, visual motion, and shape) were collected and rated on a 7-point Likert scale. Afterwards, participants of the experiment were tasked to decide a degree to which the stimulus could be experienced through these senses. The results indicated the encodement of concepts in multimodal and higher-level unimodal areas based on the corresponding aspects of chosen words in line with the grounded cognition model. In the follow-up study, Fernandino et al. (2016) used the data obtained from the questionnaire to create a multiple regression model that successfully predicted fMRI activity patterns for specific words.

In conclusion, GCM challenges the Amodal Symbolic Model by emphasizing the integration of semantic knowledge with real-world experiences grounded in sensorimotor modalities. This paradigm shift, supported by evidence from linguistics, neurology, and psychological studies, offers a more nuanced understanding of cognition, highlighting its relationship with perception, and action. Additionally, questionnaires of sensorimotor attributes of concepts are methodologically sound tools validated by previous research and there exists a valid concern, based on Pulvermüller (2023), that translated words lose their subtle cultural nuances. Acquiring sensorimotor ratings of Slovak words offers a viable and much-needed tool for investigating the effects of sensorimotor features on semantic processing applicable to the local context. Despite the apparent need for one, to our knowledge, there does not exist one yet.

Chapter 3

Neurocognitive Models

The following section seeks to introduce contemporary theories regarding the storage of concepts and the semantic retrieval process within the framework of embodied cognition.

3.1. Sensorimotor Features

Various objects in our daily lives have typical (canonical) perceptual features. Whether it's the red of an apple, the cylindrical form of a pen, or the pendulum motion of a children's swings. This commonality of sensorimotor features between the individual instances represented by concepts facilitates the objects' recognition and understanding of the world around us. E.g., Gustatory and olfactory attributes play a crucial role in defining the meanings of words related to any type of food. Furthermore, they serve as warning signals, thereby contributing to the significance of words like 'fire' and substances such as 'petrol'. The central claim of grounded cognition, that semantic processing overlaps with action and perception inspired numerous neuroscience studies, trying to figure out the extent to which conceptual processing engages modality-specific systems associated with perception and action (Kemmerer, 2014). The following section aims to present neuroimaging evidence in support of this assertion.

Zeki et al. (1991) observed heightened activity in the V4 area, situated in the posterior segment of the occipital lobe, during the passive viewing of colorful stimuli. Simmons et al. (2007) extended these findings by identifying increased activity in V4α, located in the fusiform gyrus, during the discrimination of colors. Notably, the research indicated activation of partially non-overlapping regions when subjects were verifying concept properties related to motor and color properties (Simmons et al., 2007). Further evidence comes from neuropathological investigations. Damage to various regions, including the left anterior temporal lobe (ATL), encompassing ventro-rostral portions of the lingual gyrus, isthmus, and parahippocampal areas, and occasionally left parietal damage, can result in a condition known as *color agnosia*, characterized by a selective impairment in associating objects with their canonical colors (Bartolomeo, 2022). The recognition of shapes is also closely linked to the functioning of the ventral pathway. Kozlovskiy and Rogachev (2021) exposed the participants of the EEG experiment to diverse stimuli of various shapes and colors and asked them to memorize either the color, the shape, or both attributes simultaneously. The findings discovered the involvement of the V8 area, superior to human V4, in shape perception. The intermediary VO2 area, positioned between V4 and V8 and the parahippocampal cortex, emerged as an integrator combining information about both color and shape, contributing to forming a comprehensive and holistic visual image. The cortical regions linked to higher-order perception of non-linguistic environmental sounds substantially overlap with those involved in higher-order speech perception, encompassing the superior temporal gyrus (pSTG), superior temporal sulcus (pSTS), and posterior middle temporal gyrus (pMTG) in both hemispheres. However, fMRI studies indicate a left-lateralized bias in perceiving speech compared to non-linguistic environmental sounds (Dick et al., 2007). Trumpp et al. (2013) demonstrate the crucial role of the left pSTG/MTG in handling sound-related concepts associated with everyday objects. Neurological evidence indicates that injuries affecting this segment of the auditory association cortex not only hinder the recognition of actual sounds but also impair the processing of everyday concepts where sound attributes play a significant role, such as 'telephone' or 'bell'. Smell and taste perception exhibit similarities, as they both originate from chemical receptors. This shared foundation extends to higher levels of processing, as both types of perception are recognized to rely on the bilateral involvement of the orbitofrontal cortex (Rolls, 2023; Small et al., 2007). Additionally, through the process of learning, visual inputs become linked in the orbitofrontal cortex with the taste of food, creating a representation of the visual aspect of food and contributing to the overall flavor perception (Rolls, 2023). However, It remains uncertain whether these instances signify mental simulation or mental imagery (Speed & Majid, 2019).

There exists strong evidence from neuropathology and fMRI studies in support of the central tenet of GCM, that semantic processing re-uses modality-specific sensory and motor features stored in long-term memory through mental simulations. On the other hand, as pointed out by Speed and Majid (2019) further research is needed to determine whether the perception of concepts associated with olfactory and gustatory experiences aligns with the GCM.

3.2. Controlled Semantic Cognition

Several pieces of neuroanatomical evidence support the idea that concepts are stored in the distributed sensorimotor regions of the brain. However, the connectivity of anatomically distributed modality-specific features and the mechanisms by which perceptual features belong to a given concept, while others are excluded, remains a pivotal question. Ralph et al. (2017) introduced a comprehensive framework known as Controlled Semantic Cognition (CSC) consistent with the GCM. CSC aims to explain how the brain facilitates the utilization of semantic knowledge. The model relies on two interacting but to a large extent independent neural systems. The first system, responsible for the representation, encodes concepts through higher-order relations among various sensorimotor, linguistic, and affective features in the cortex. The second system serves as a control mechanism, manipulating activation within the representational system to produce suitable behavior and deductive reasoning (Ralph et al., 2017).

3.2.1 Semantic representation

The system of semantic representation is largely based on the 'hub-and-spoke' theory proposed in review by Patterson et al. (2007). As shown on **Figure 2.1**, the view proposes that semantic representation consists of a central 'hub' located anterior temporal lobe (ATL) and various 'spokes' representing modality-specific areas. Before that, several 'hubless' theories of semantic representation were developed (Mahon & Caramazza, 2011; Tranel et al., 1997). Tranel et al. (1997) proposed that the distributed interconnected modality-specific regions form the entire neural basis of semantic memory and the associations between pairs of attributes are encoded along different neuroanatomical pathways without the need for a convergence hub. A recent paper by Ding et al. (2020) aimed to develop a comprehensive model of semantic dementia (SD) by analyzing a large case series with varying patterns of atrophy in the ATL by utilizing multiple regression analyses and principal component analysis. The results revealed that the severity of general semantic impairment in SD was correlated with bilateral ATL atrophy. These observations suggest that fundamental semantic abilities, such as information transfer between modalities and differentiation between conceptually similar entities depend on the ATL and thereby support the existence of a semantic 'hub' in this area, lending further support to the 'hub-and-spoke' theory.

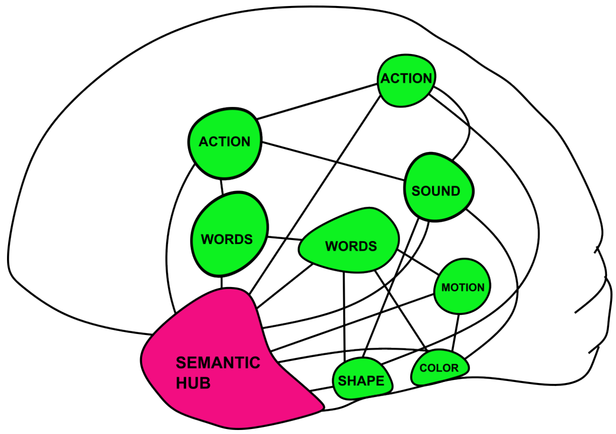

Figure 3.1: 'Hub-and-spoke' theory of semantic representation (based on illustration from Patterson et al., 2007)

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3.2.2 Semantic control

The semantic representation system operates by automatically retrieving information triggered by environmental cues or spontaneous thoughts (Badre & Wagner, 2007). However, in our everyday lives, it's essential to regulate and oversee the activity within this network for optimal decision-making. This ensures that the system produces representations and conclusions tailored to the specific task or context. Ralph et al. (2017), proposed that the control of semantic cognition is implemented within a distributed neural network interacting with, but to a large extent independent from the network responsible for semantic representation.

A recent meta-analysis of fMRI evidence, conducted by Jackson (2021) found that semantic control relies on a distributed network comprising the left inferior frontal gyrus (IFG), posterior middle temporal gyrus (MTG), posterior inferior temporal gyrus (ITG), and dorsomedial PFC (dmPFC). This network exhibits a left-dominant pattern, demonstrating an increased level of involvement of the left IFG compared to the right IFG. Badre and Wagner (2007) proposed two cognitive control mechanisms. *Controlled retrieval*, supported by left anterior VLPFC and *post-retrieval selection* by mid-VLPFC. Controlled retrieval is necessary in case the relevant semantic information is not automatically activated during a retrieval attempt. In such situations, a control mechanism that preserves relevant cues may introduce a top-down influence, promoting the retrieval of relevant knowledge. *Post-retrieval selection* on the other hand serves to resolve the competition between simultaneously active representations (Badre & Wagner, 2007).

The advancements in the understanding of controlled and automatic systems of semantic cognition led to the need for new behavioral assessment tools. Marko et al. (2024) developed *associative-dissociative retrieval* task (ADT). During the ADT, participants are sequentially presented with word stimuli and asked to generate a word response based on one of the two conditions. In the *free-associative* condition (FA), participants are required to answer with the first word related to the stimulus that comes to mind. Conversely, in the *dissociative* condition (DA) participants generate unrelated words to the presented stimuli. The DA demands significantly more processing time compared to FA, which has been attributed to the suppression of automatically evoked prepotent associations (Marko & Riečanský, 2021; Marko et al., 2024). Moreover, the task allows the computation of the *inhibition cost* (IC), which is calculated as the latency difference between the two tasks (IC = DA - FA). The inhibition cost metric operates under the premise that both FA and DA entail various stages, with some of them being common to both conditions, such as reading, lexical access, and responding. Thus, subtracting the mean retrieval latencies helps eliminate the processing cost of the shared stages, allowing for the estimation of the processing time required for the specific functions of semantic control.

The CSC model of semantic cognition has garnered widespread support in recent years, backed by substantial evidence from neuroimaging and neuropathology. Nevertheless, open questions remain about the nature of concepts. Such as the ways abstract concepts emerge from a set of semantic features located in modality-specific spokes interconnected via a semantic hub. In the next section, we will focus on the problem of the acquisition and processing of abstract words from an interdisciplinary perspective.

Chapter 4

Abstract Concepts

In the previous part, we have presented numerous evidence demonstrating that sensory and motor sensations are necessary for concept acquisition and play an important role during semantic memory processing. At the same time, it is not clear, that abstract words have a direct association with our senses, as they refer to objects with ambiguous or sometimes no physical references (Borghi & Binkofski, 2014). One example of a word without a clear link to sensorimotor features is 'justice'. Justice is a complex concept combining notions of fairness, morality, and the fair treatment of individuals. While people generally have a conceptual understanding of justice, it is unclear how this concept can be directly derived from concrete sensory experiences or motor actions. Moreover, it is noteworthy that not only do embodied approaches face challenges in explaining abstract concepts, but all theories of semantic processing, including amodal ones, struggle to provide a satisfying explanation for the abstract concepts (Barsalou, 2020).

One of the earliest models addressing the distinction between abstract and concrete concepts was introduced by Allan Paivio in the 1970s, known as the Dual-Coding Theory (Paivio, 2013). According to this theory, information is processed and stored in two complementary codes: a symbolic code and an analog code involving imagery. Paivio observed improved memory retention of concrete concepts, referred to as *concreteness advantage*. The DCT explains this phenomenon based on the assumption, that concrete concepts are represented in both analog and symbolic codes, which facilitates semantic retrieval. Conversely, abstract concepts, lack imagery analog codes, therefore they present a challenge for semantic retrieval. As illustrated in **Figure 4.1**, Pulvermüller (2023) suggests a distinctive structural contrast between concrete and abstract concepts. Concrete concepts, exemplified by concrete entities like 'dog,' incorporate shared semantic features that apply to all members within the respective category. Conversely, abstract concepts, such as 'beauty,' apply to objects and entities that exhibit considerable diversity in semantic features, yet display a *family resemblance* characterized by the partial sharing of features across different instances. Furthermore, multiple lines of interdisciplinary evidence indicate that the abstractness of concepts is not a binary characteristic but, rather, a nuanced and graded one with concepts exhibiting varying degrees of abstractness (Reinboth & Farkaš, 2022). According to a review article by Reinboth and Farkaš (2022) all concepts are acquired through two pathways. The primary pathway involves direct engagement with the body, encompassing sensorimotor interactions with the environment, interoception, and emotional experiences. Simultaneously, a secondary pathway operates indirectly through communication processes, such as linguistic and social interactions. Furthermore, contemporary research proposes that abstractness should not be perceived as a unidimensional scale. Instead, it appears to manifest as a combination of diverse attributes across various modalities, not traditionally taken into account in the Grounded Cognition Model, such as social dynamics, emotional experiences, and more (Conca et al., 2021).

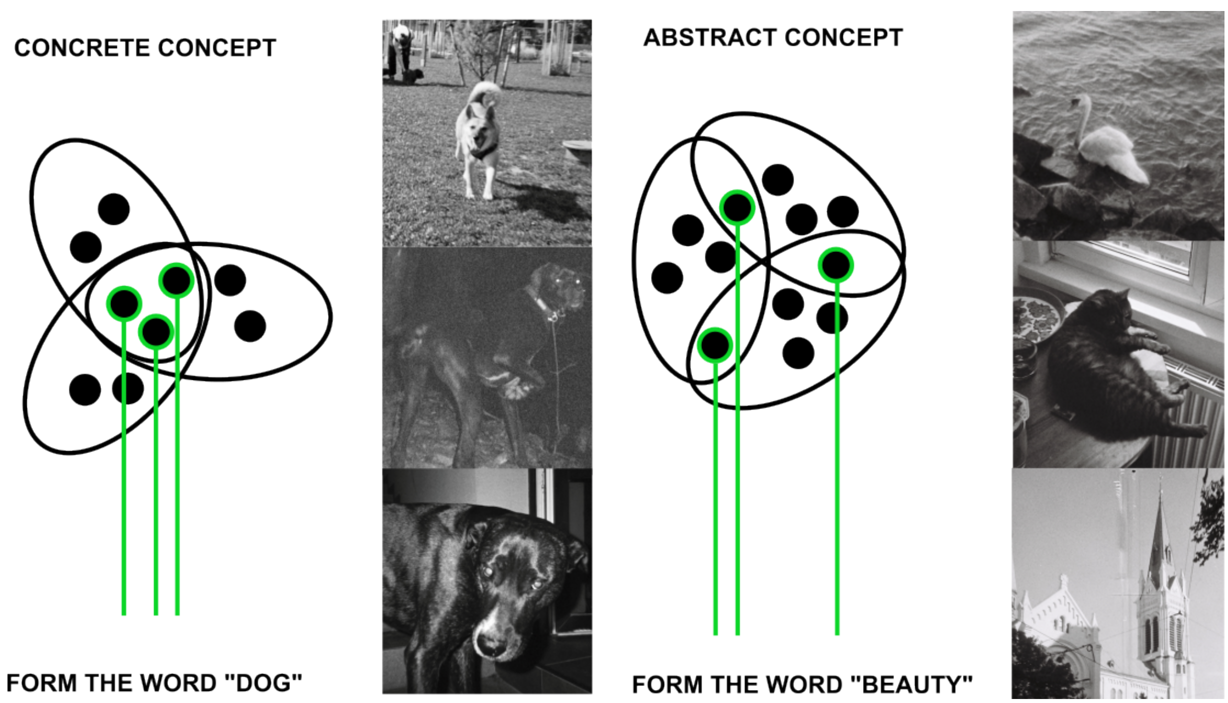

Figure 4.1: Abstract concepts usually lack universally shared semantic features, instead they commonly exhibit a pattern of family resemblance (based on illustration from Pulvermüller, 2023)

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A meta-analysis conducted by Wang et al. (2010) of fMRI studies including various cognitive assessments of semantic cognition (such as lexical decision, word recognition,

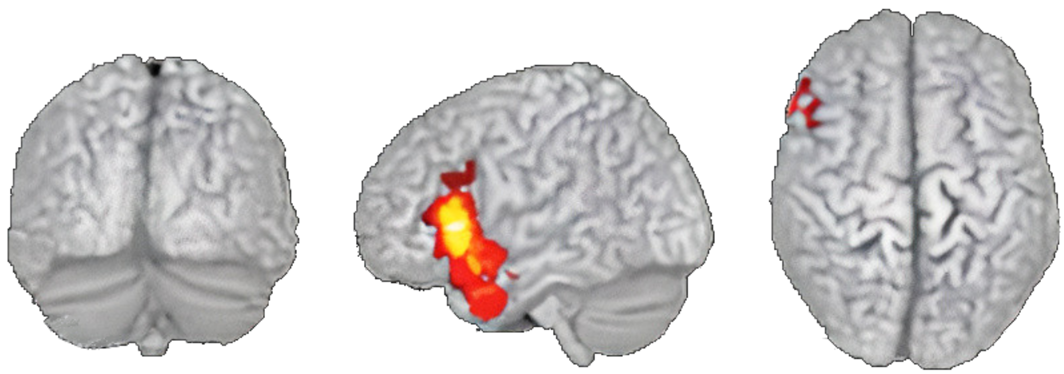


Figure 4.2: Regions with significant proportions of stronger activation for abstract compared to concrete concepts. (Modified from Wang et al., 2010)

passive listening, etc.) revealed distinct neural representation patterns for abstract and concrete concepts. As seen in **Figure 4.2**, regions exhibiting significantly stronger activation for abstract concepts, as opposed to concrete ones, were identified in the left hemisphere's inferior frontal gyrus (IFG) and middle temporal gyrus (MTG). The anterior inferior segment of the IFG, along with the broader prefrontal regions, has been associated with verbally mediated semantic knowledge processing. Hoffman et al. (2015) conducted an fMRI study, focused on the distinct involvement of IFG and ATL in concrete and abstract semantic processing. The participants underwent a synonym judgment task. In each trial, participants were presented with a word stimuli, and a semantically related target along with two unrelated choices displayed below it. Afterward, they were asked to select the word that was most similar in meaning to the probe. Moreover, before each trial, participants were presented with a cue consisting of two short sentences. In half of the trials, the probe word was placed at the end of the sentence and presented in a meaningful context. The outcomes of the experiment showed, that the left IFG and superior and ventral ATL areas showed greater activation for abstract words relative to concrete ones. Interestingly, the response varied across contexts and IFG displayed maximal response when cues were irrelevant to the probe, suggesting increased involvement during tasks demanding higher semantic control. Furthermore, Bowman and Zeithamova (2018) model-based fMRI investigation provides compelling evidence supporting the idea that the ventromedial PFC (VMPFC) and anterior hippocampus, part thought to be responsible for formation, consolidation, and retrieval of declarative memories, play a crucial role in representing abstract concepts during the process of concept generalization. The findings suggest that the integration mechanisms between the VMPFC and hippocampus contribute significantly to the generalization of knowledge across various cognitive domains. In a recent neuroimaging study by Vignali et al. (2023) participants were sequentially presented with word stimuli and asked to answer the question: 'Was it a word related to the senses?' Interestingly, while fusiform and occipitotemporal regions showed activation to concrete concepts only, contrary to Wang et al. (2010) no brain region showed greater activation for abstract compared to concrete concepts. Moreover, the neuroimaging technique used by Vignali et al. (2023) showed that the activation of fusiform and lateral occipitotemporal cortex happens approximately 700 milliseconds after the reading of the word, indicating a delayed activation of the sensorimotor/imagistic code in the course of semantic processing.

Overall, abundant evidence shows that the acquisition of abstract concepts operates via the interaction with the environment. Furthermore, multiple sources of evidence provide support for the idea, that left PFC plays a more significant role during the processing of abstract compared to concrete concepts; and that this involvement is amplified by semantic control demands. Nevertheless, the exact neural underpinnings of abstract concepts and the role of re-enactment and mental imagery in semantic processing remain unclear, and the mixed results facilitate the need for further research.

Chapter 5

Neuromodulation of Semantic Cognition

While fMRI enjoys widespread recognition as an advanced neuroimaging method, there has been a surge of interest in an alternative methodology using Transcranial direct current stimulation (tDCS) - one of the contemporary brain modulation techniques. Brain stimulation techniques consist of various tools used to alter the brain's activity for therapeutic or research purposes. In particular, tDCS involves the application of a low electrical current to the scalp through electrodes.

5.1. Transcranial Electrical Stimulation

In the 1960's, researchers started experimenting with the technique of neuromodulation by the application of weak direct current directly to the neuron membranes and subsequently to the animal scalps (Albert, 1966; Bindman et al., 1964; Bindman et al., 1962; Terzuolo & Bullock, 1956). Lippold and Redfearn (1964) motivated by the research done on the animals, set up an experiment where they put a polarizing electrode above each eyebrow, and the indifferent electrode was placed above the right knee. They observed mental changes of an elevation of mood and increased involvement in the environment during anodal stimulation. Conversely, cathodal stimulation led to withdrawal and quietness of the participants. Despite the early results, the research was largely abandoned until the start of the 21st century (Nitsche & Paulus, 2000). Transcranial direct current stimulation has since garnered considerable attention as a noninvasive neuromodulation technique used for addressing a spectrum of brain and mental disorders. This method involves delivering a low-amplitude current (typically up to 2 mA) for a brief period, not exceeding 30 minutes, through saline-soaked sponge-covered rubber electrodes. Placing at least one electrode on the scalp allows electric currents to penetrate the skull, influencing spontaneous neural activities underneath (Yokoi et al., 2017). The modulatory effects of tDCS potentially offer a therapeutic tool for the treatment of depression and psychosis (Yokoi et al., 2017).

The application of anodal tDCS at intensities of 1–2 mA alone lacks the potency to sufficiently depolarize neuronal membrane potentials to reach the firing threshold, and therefore only increases the excitability and the rate of spontaneous firing of neurons. In contrast, cathodal stimulation is thought to decrease the resting membrane potential, thereby interfering with the depolarization processes. This effect reduces spontaneous firing and consequently leads to a reduction in neuronal excitability (Nitsche & Paulus, 2000). At the biochemical level, anodal stimulation facilitates excitatory synaptic transmissions through the stimulation of glutamate pathways and the inhibition of GABA transmissions. Additionally, it modulates the dopamine system, boosts serotonin transmissions, and suppresses acetylcholine transmissions. In this manner, the effects of the stimulation may extend from the stimulated site and modify the activity levels of various network systems (Yamada & Sumiyoshi, 2021). Furthermore, there is increasing evidence that tDCS modulates the Long-Term Potentiation and Long-Term Depression - lasting strengthening and weakening of synaptic connections between neurons, respectively (Frase et al., 2021; Kronberg et al., 2017; Watanabe et al., 2023).

Previous research suggests that tDCS possesses an ability to modulate larger brain circuits by the release of various neurotransmitters and initiating lasting changes through LTD and LTP. Nevertheless, additional research is still needed to fully understand its mechanism of action and to unlock its potential applications in cognitive enhancement, rehabilitation, and treatment of neuropsychiatric disorders.

5.2. Effects of tDCS on Semantic Cognition

There is an ongoing increase in cognitive neuroscience studies that utilize tDCS for neuroimaging purposes. This neuromodulation technique can be applied during cognitive assessments to observe alterations in neural activation patterns, functional connectivity, and information processing (Pisoni et al., 2017). By comparing the neuroimaging data of individuals who receive tDCS to those who undergo sham stimulation, researchers can identify brain regions responsible for specific cognitive functions.

Joyal and Fecteau (2016) meta-analysis of tDCS studies concluded, that tDCS applied over frontal, temporal, and parietal cortices is capable of influencing semantic cognition. The tDCS modulated semantic processing in 23 out of 32 experimental studies when administered to the frontal cortex, and in 6 out of 9 experimental scenarios when applied to the temporal and parietal cortices. Fertonani et al. (2010) showed that anodal stimulation of the left dorsolateral PFC improves picture naming. Furthermore, improvement in verbal fluency was also observed (Cattaneo et al., 2011; Meinzer et al., 2012; Pisoni et al., 2017).

Pisoni et al. (2017) implemented a study involving tDCS with the anode positioned over the left inferior frontal gyrus (LIFG), and the cathode situated over the right supraorbital region. Stimulation lasted for 20 minutes, including a 30-second fade-in/fade-out period. Participants engaged in a verbal fluency task across three sessions, each consisting of two semantic judgments and two verbal fluency tasks. In these tasks, participants were instructed to generate as many words as possible within one minute, either beginning with a designated letter or falling within a predefined semantic category. The results of the experiment showed, that anodal tDCS applied over LIFG increased verbal fluency performance. Marko and Riečanský (2021) performed a tDCS study on 121 participants, separated into three different groups: one with an anode placed over the left lateral PFC, a control group with anode placed over the temporoparietal cortex, or sham stimulation and requested the participants to perform an *associative chain test* (ACT). During the cognitive assessment, participants were asked to continuously produce either *associative* word chains, where each word is semantically related to the previous one, or *dissociative* chains, where each new response is not related to the previous one (Marko et al., 2018). Marko and Riečanský (2021) observed that excitatory tDCS applied to the left lateral PFC improved the performance on controlled semantic retrieval task (dissociative chains), but not automatic semantic processing (associative word chains). Additionally, Gnedykh et al. (2022) found that applying either cathodal or anodal tDCS over Broca's region improved contextual learning of novel words, supporting the involvement of Broca's area in word acquisition. More interestingly, the improvements in word recognition were the most expressed for abstract words.

In recent years, there has been an increase in neuroimaging research of semantic cognition incorporating tDCS. Converging evidence suggests that tDCS targeting PFC can modulate semantic memory processing, and conceptual retrieval in particular. However, to our knowledge, no tDCS study has explicitly investigated the role of the left lateral PFC in the semantic processing of words with differentiation between abstract and concrete words, especially concerning controlled and automatic retrieval. This paper aims to bridge this research gap.

Chapter 6

Present Research

Grounded cognition posits that semantic memory retrieval is linked to our sensorimotor experiences. This study examined the role of sensorimotor features of concepts, specifically investigating the role of the left prefrontal cortex (PFC) in retrieval processes and its connection to the sensorimotor grounding of concepts. While previous research within the grounded cognition paradigm has gathered a substantial amount of evidence in favor of this theory, a key question remains: To what extent does the degree of sensorimotor grounding of concepts influence how we retrieve them from semantic memory?

The current study addresses this gap by employing a questionnaire focused on sensorimotor ratings of words of various levels of concreteness and abstractness. We collected sensorimotor ratings of words in 7 features (shape, color, sound, manipulation, motion, smell, taste). Next, we employed the results in a cognitive assessment experiment. Participants underwent ADT test (Marko et al., 2024) designed to assess their performance on automatic (free-associative trials) and controlled (dissociative trials) semantic memory retrieval. Participants were continuously presented with a word stimuli and tasked to come up with a related answer during the free-associative (FA) condition and to respond with an unrelated word during the dissociative (DA) condition. Moreover, to elucidate the role of left VLPFC (a region heavily implicated in semantic processing) we employed transcranial direct-current stimulation (tDCS).

Based on the previous research, we predicted that the degree of sensorimotor grounding will decrease the RT for the FA condition. However, since the dissociative condition requires inhibition of automatically activated sensorimotor features, we expected that higher levels of sensorimotor grounding would not facilitate the retrieval of unrelated responses during the DA trials. Furthermore, we predicted that applying (tDCS) to PFC will improve the performance during the DA condition. Since retrieving free associates represents a predominantly automatic and spontaneous process with low explicit constraints and control demands, we did not expect the tDCS to affect the FA condition of the ADT task.

Finally, due to the proposed role of PFC in the processing of abstract concepts and abstract thought in general, we predicted that tDCS will be more effective at improving RT for abstract words compared to concrete concepts, in both FA and DA retrieval tasks.

Chapter 7

Methods

7.1. Participants and study design

The study utilized a double-blind randomized placebo-controlled experimental design with one between-subjects factor (*Stimulation:* Sham, PFC) and two within-subjects factor (*Measurement:* Pretest, Posttest;*EMB:* Abstract, Concrete). The outline of the main experimental procedure is depicted in **Figure 7.1a**. The sample size was determined by considering previous studies with similar designs and outcome measures, along with the necessity to attain sufficient statistical power ($1 - \beta = .80$ at $\alpha = .05$) to detect effect sizes that are both theoretically and clinically significant—following Cohen's recommended criteria (Cohen, 1992), which suggests an effect size of $r \geq 0.3$ for simple correlations or $d \geq 0.5$ for between-group comparisons. A total of 80 participants (29 males; age 23.0 ± 3.6) participated in the experiment during a single neuro-stimulation session out of which 10 were employed full-time, 4 were employed part-time, 36 were students and 30 were working students. The participants were pseudo-randomly assigned to either the stimulation ($n = 40$) or the control group ($n = 40$).

Participants were right-handed monolingual native Slovak speakers with normal or corrected to normal vision; with no history of psychiatric, neurological, or other significant medical conditions that could affect cognition; and were not currently taking any mind-altering medication. Right-handedness was assessed by the Edinburgh Handedness Inventory - short form (Veale, 2013; mean score 90.5 ± 14.8). Additionally, participants were asked to abstain from alcohol at least 24 hours before the session and to keep their typical caffeine and nicotine consumption. The study adhered to the principles outlined in the Declaration of Helsinki by World Medical Association (2013) and obtained approval from the institutional review board. Protocols and methodologies strictly followed all relevant guidelines and regulations. Before participation, all individuals provided their written informed consent and received financial compensation for their time and effort after their involvement in the experimental session.

7.2. Sensorimotor Questionnaire

A separate sample group of 28 participants (14 males, $age = 27.46 \pm 9.03$), out of which 17 were students and 11 were employed, was recruited to fill out an online questionnaire on sensorimotor ratings. Participants were asked to rate 178 words based on the relevance of the 7 sensorimotor categories (shape, color, movement, manipulation, sound, smell, taste) for the meaning of the word on a 7-point Likert scale ranging from 'The given attribute is not significant for this word at all' = 0 to 'The given attribute is highly salient for this word' = 6. Afterward, the ratings for each sensorimotor feature were averaged. To maintain comparability against the previous studies in a similar matter (Marko & Riečanský, 2021; Marko et al., 2024) we selected 10 abstract and 30 concrete words. The differentiation between abstract and concrete words represented additional within-subject factors of the study. Finally, each participant received financial compensation for the time and effort invested upon completion of the questionnaire.

7.3. Design and Procedure

Individual sessions were conducted between 9 AM and 5 PM. Each trial started with a brief anamnestic interview, followed by the administration of self-reported measures and control cognitive tasks focused on general retrieval ability (gR) (Carroll, 1993). Subsequently, participants were seated at the main lab, where tDCS and ECG electrodes[1] were mounted and configured. The main experiment started with a comprehensive practice run allowing participants to become thoroughly acquainted with the experimental tasks and procedures. Following this, ECG measurements started with participants resting for a minimum of 5 minutes. After the resting period, the pretest measurement was conducted. Following a short break, tDCS stimulation began, during which participants reported perceived adverse effects of the stimulation, followed by the post-test measurement. Participants were prompted to indicate their current affective and motivational state using dedicated analog rating scales at the beginning and end of all measurement blocks. Finally, after completing the posttest measurement, tDCS stimulation and ECG recording were terminated, and a brief debriefing session was conducted.

[1]The ECG was recorded but not subjected to analysis in this study.

7.4. tDCS

tDCS was delivered by a battery-driven, constant current stimulator (Eldith, Neuroconn, Ilmenau, Germany) through one anodal and two cathodal conductive rubber electrodes ($3cm \times 3cm : 9cm^2$) attached to the scalp using an EEG cap, elastic bands, and conductive electrode paste (Ten20, Weaver and Co., Aurora, CO, USA). As depicted in **Figure 7.1b**, the anode was placed between F5 and F7, and the cathodes were placed on Cz and F2 sites of the international 10-10 system of EEG electrode placement.

Electric field intensity models decided the placements of electrodes estimated in SimNibs v3.1 (Saturnino et al., 2019) to achieve peak levels of polarization with ventrolateral PFC. The results of the simulation are displayed on the **Figure 7.1c**. The stimulation intensity was set to $2mA$ and delivered for 20 minutes along with a one minute ramp-up and one-minute ramp-down period for the stimulation group. The stimulation of the control group consisted of a 60-second ramp-up period, however, the full-intensity current was delivered only for 40 seconds. The impedance during the stimulation was kept below $10k\Omega$.

7.5. Cognitive Assessment

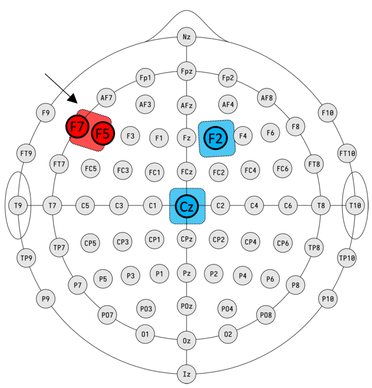
7.5.1 Entrance Examination

Before the main experimental phase, participants underwent a series of standard verbal fluency tasks to assess their general retrieval ability (gR) as a control cognitive measure. These tasks comprised three trials each, following a fixed order: phonemic fluency (listing words starting with 'K', 'D', and 'F'), semantic fluency (naming items from categories such as 'Occupations', 'Animals', and 'Electrical Appliances'), feature fluency (identifying items that are 'Red', 'Loud', and 'Round'), and word fluency (listing words without specific letters such as 'K and/or P', 'R and/or S', and 'A and/or E'). An independent samples t-test found no significant difference between the two groups on scores of the gR task ($t(77.2) = -0.015$, $p = .95$), suggesting no significant differences in general retrievability.

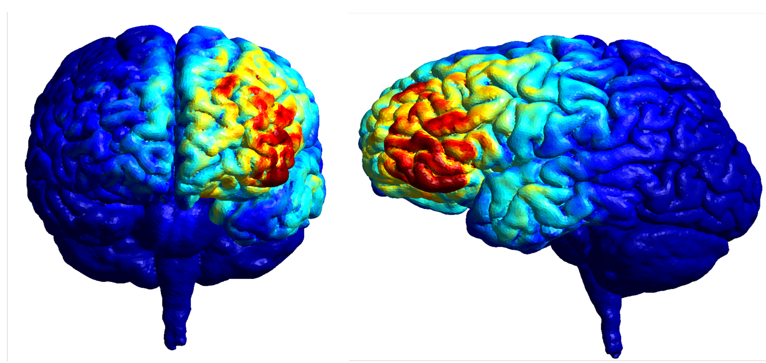
7.5.2 Semantic Memory Retrieval

Semantic memory retrieval and controlled retrieval were assessed by the modified version of ADT test (Marko et al., 2024). Participants were seated in front of a computer screen and presented with a series of words and non-words words one at a time, in a pseudorandom order. First, in the lexical decision task (LDT) participants simply had to decide if each

(a) Timeline of the experimental session. The session was initiated with a block including a short anamnestic interview, an assessment of verbal fluency (gR), and a CAPE questionnaire (IA). Cognitive tests were administered in three blocks: Practice, Pretest, and Posttest). There was a 5-minute break between each cognitive test (B). Afterwards, a short debriefing session ensued (Debrief).



(b) Schematic depiction of electrode placement. The anode (red) and cathode (blue) are plotted for positions of the 10-10 system.



(c) Simulated electric field intensity for tDCS.

Figure 7.1: Experimental procedure and tDCS

item was a real word. If it was, the word changed color to either green or red. In the green condition (FA), participants engaged in free association, instructed to type the first common noun that came to their mind by the presented stimulus. Conversely, if the word was presented in red color participants were asked to type in a common noun unrelated to the presented stimuli (DA condition). Following every DA trial, participants were asked to report intrusions - a spontaneous emergence of a related word during the generation of an unrelated word [2]. Furthermore, participants were asked to retrieve words in both conditions as fast as possible and accurately; to not simplify the task with tricks or strategies, such as naming objects in the room or preparing answers in advance; and to try to minimize excessive repetition of the same words. Additionally, participants were given a one-minute break after every block of 20 words. During this break, they were instructed to rest and focus on the center of the screen. Participants underwent three separate assessment blocks during one experimental session. In the first (practice) trial, participants were presented with 20 words and 20 non-words. The main experimental assessment included a *Pretest* and *Posttest* block, in which participants were presented with 40 words and 40 non-words. Each word was presented in both FA and DA conditions (i.e., each experimental block included a total of 80 trials).

After the experiment, each response was rated by three independent raters on a Likert scale from 'Completely Unrelated' = 0 to 'Prepotent' = 5 (see **Table 7.1** for complete instructions). Responses with an average rating above 2.5 were evaluated as errors in the DA condition and correct in the FA condition. Conversely, responses with an average rating below 2.5 were evaluated as errors in the DA condition and correct in the FA condition. Additionally, omissions, illegible responses, and words categorized as other than nouns, along with proper nouns were evaluated as errors.

7.6. Self-reported measures

Before the main experiment, participants underwent the Community Assessment of Psychic Experiences (CAPE) (Stefanis et al., 2002; Slovak version by Forgáčová et al., 2019). This questionnaire was designed to assess various psychic experiences that individuals and detect individuals at an increased risk for developing psychosis (Kiang et al., 2010; Merten, 1993). An independent samples t-test found no significant difference between the two groups on CAPE scores ($t(74.7) = -0.015, p = .947$).

[2] This measure was not addressed in the present study.

Relatedness	Rating	Description
Completely unrelated	0	It is very hard to find a meaningful link between the words, even if one tries and considers unlikely themes and/or scenarios. This is considered an excellent dissociation.
Unrelated	1	The stimulus and response are generally unrelated. This is considered a good/default dissociation.
Remote	2	There is only very weak/remote and/or indirect link between the words. This is still considered a sufficient dissociation.
Weakly related	3	Weak or less common association. This is considered a sufficient association.
Related	4	The response is a common association with a clear link to the stimulus. This is considered a good/default association.
Prepotent	5	A strong and dominant association most people deliver. This is considered a prepotent association.

Table 7.1: The semantic relatedness scale was used by the independent raters to evaluate the semantic relatedness between stimuli and responses. Responses with an average relatedness rating above 2.5 were considered errors in the DA condition and correct for the FA condition and vice versa for the responses with a rating below 2.5.

Additionally, the psychological state of participants was assessed both before and after each measurement block (Pretest and Posttest) using a specialized scale. The ordinal scale comprised 16 items aimed at capturing various affective and motivational states. These states were categorized into four distinct dimensions: *positive* affect ('joy', 'ease', 'confidence', and 'calm'), *negative* affect ('anxiety', 'tension', 'stress', and 'nervousness'), *vigilance* ('arousal', 'attentiveness', 'fatigue', and 'sleepiness'), and *motivation* ('commitment', 'eagerness', 'excitement', and 'interest').

Furthermore, participants were asked to sequentially report the perceived intensity of adverse effects every 30 seconds using 6 seemingly analog sliders (itching, pinching, tingling, burning, tickling, pain; 'not at all' = 0, 'very much' = 100) during the 60-second ramp-up period and first two minutes of full-intensity tDCS. Results were averaged to assess the global adverse effects in time.

Finally, each participant and task administrator were asked to guess whether the participant received sham or verum tDCS. The chi-square test results indicated, that neither the participants ($\chi^2(1) = 0.251$, $p = .617$) nor the researchers ($\chi^2(1) = 0.224$, $p = .636$) were able to guess who received the real stimulation accurately.

7.7. Statistical analysis

The initial analysis revealed outliers in the retrieval time (RT) characterized by positive skewness. These outliers fell outside 1.5 interquartile ranges below $Q1$ or above $Q3$. Therefore, the RTs were winsorized (10% two-sided trimming by participant and retrieval condition) and assessed using generalized linear mixed effect models (GLMEMs) with gamma distribution and identity link function. The models were fitted by maximum likelihood and unstructured random-effects covariance matrix. Type II Wald χ^2 test estimated the p-values for the fixed effects. GLMEM evaluated the main hypotheses including one between-subjects faction (*tDCS*; Sham, PFC), and two within-subjects factors (*Block:* Pretest, Posttest; *EMB:* Concrete, Abstract).

Chapter 8

Results

8.1. Self-reported measures

8.1.1 Psychological state

As shown in **Figure 8.1**, a repeated-measures ANOVA was conducted on the affective responses collected after each measurement block, to investigate how the psychological state of participants changed throughout the experiment. The results in **Table 8.1** revealed a significant effect of measurement ($F(3, 231) = 6.062$, $p < .001$, $\eta_p^2 = .073$), indicating the psychological state changed across trails. There was no significant effect of tDCS ($F(1, 231) = 1.198$, $p = .311$) or interaction between measurement and tDCS ($F(9, 693) = 0.644$, $p = .760$), suggesting tDCS did not have an overall effect on the psychological state. Additionally, the analysis of between-subjects effects (see **Table 8.2**) revealed that groups did not differ significantly based on the psychological state ($F(1, 231) = 0.167$, $p = .684$, $\eta_p^2 = .002$).

8.1.2 Adverse effects

Repeated Measures ANOVA showed there was a significant effect of time ($F(5, 380) = 34.84$, $p < .001$) on the adverse effects of stimulation (see **Figure 8.2**). Furthermore, there was a significant interaction effect between time and group ($F(5, 380) = 3.47$, $p = .004$), which suggests that the effect of time on adverse effects differed between the PFC and SHAM groups. Therefore, post hoc analysis was conducted to test, whether the level of adverse effect impacted the performance on LDT and ADT tasks. Principal component analysis (PCA) was used to combine several adverse ratings into a single score (PCA_{AE}). The PCA (see **Table 8.3** for components loadings) revealed a single dominant factor explaining a substantial 68% of the variance in adverse ratings. Independent samples T-Test demonstrates no significant difference in adverse ratings (captured by PCA_{AE}) between the PFC and SHAM groups ($t(76.0) = 0.948$, $p = .948$). Additionally, the weak

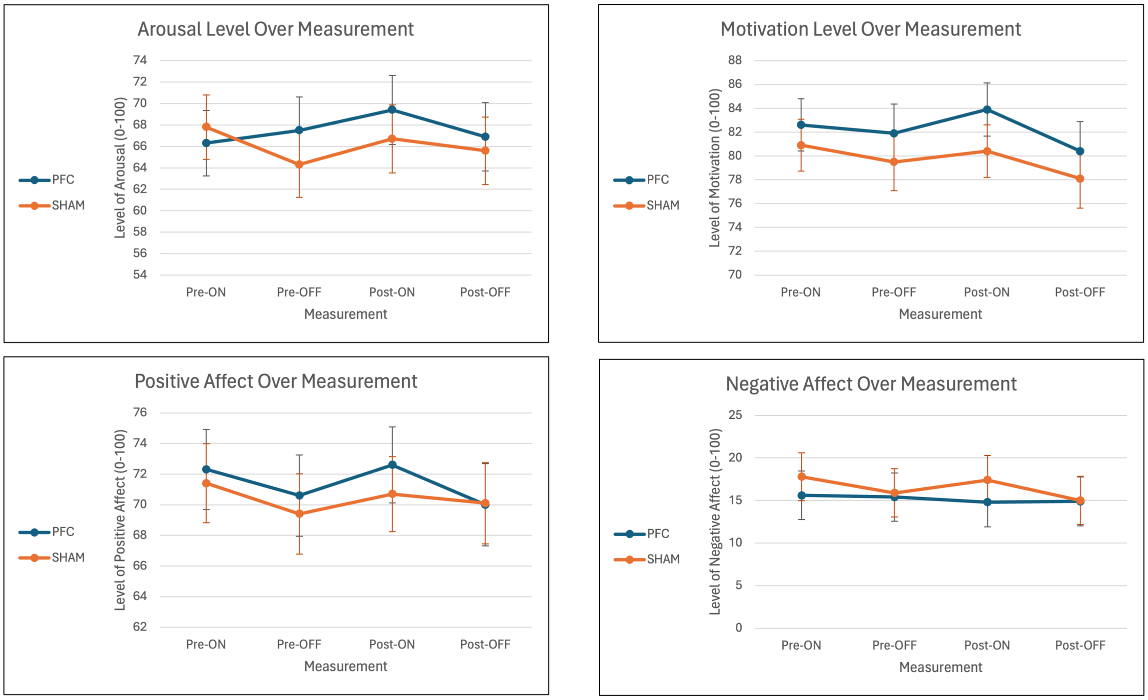


Figure 8.1: Timeline of Affective Responses after Each Measurement Block

	SS	df	MS	F	p	η^2
Measurement	814	3	271.2	6.062	$< .001$	.073
Measurement × tDCS	161	3	53.6	1.198	.311	.015
Residual	10336	231	44.7			
Component	804510	3	268170.2	279.623	$< .001$	.784
Component × tDCS	629	3	209.6	0.219	.883	.003
Residual	221539	231	959.0			
Measurement × Component	174	9	19.3	0.644	.760	.008
Measurement × Component × tDCS	260	9	28.9	0.962	.471	.012
Residual	20791	693	30.0			

Note. Type 3 Sums of Squares

Table 8.1: Repeated-Measures ANOVA Results for Psychological State over Time

Source	SS	df	MS	F	p	η^2
tDCS	244	1	244	0.167	.684	.002
Residual	112884	77	1466			

Note. Type 3 Sums of Squares

Table 8.2: Between-Subjects Effect of tDCS on Psychological State over Time

correlations between PCA_{AE} and memory task performance variables suggest that the severity of adverse effects did not have a significant impact on memory performance in this study (see **Table 8.4**).

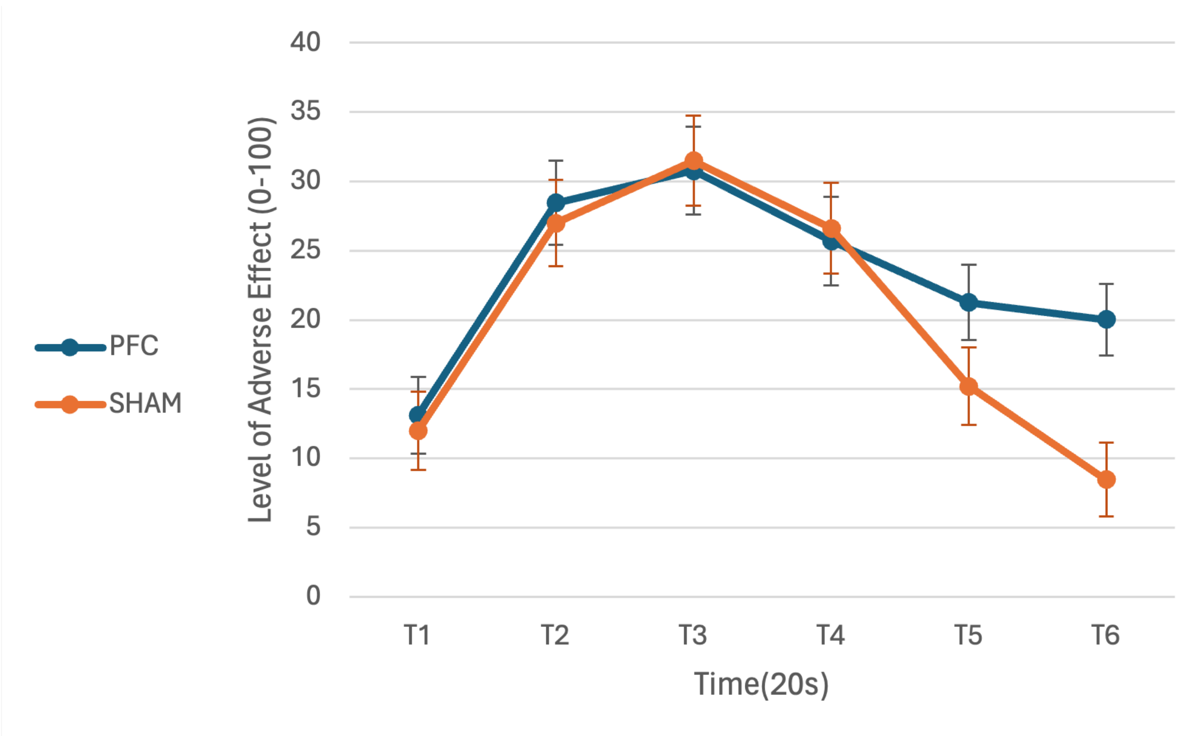


Figure 8.2: Timeline of Mean Adverse Effects of Stimulation During

8.2. Cognitive assesment

8.2.1 Semantic relatedness

We employed a GLMM analysis to investigate the influence of retrieval conditions on semantic relatedness (SR) in pretest data. The ANOVA analysis of the deviance ta-

Adverse Rating	**Component**	**Uniqueness**
1	0.502	0.748
2	0.867	0.248
3	0.898	0.194
4	0.902	0.186
5	0.895	0.199
6	0.811	0.342

Note. 'oblimin' rotation was used

Table 8.3: Principal Component Loadings from PCA Analysis of Adverse Effects

Measurement	**Task**	PCA_{AE}
Pretest	LDT_{NonW}	-0.038
Pretest	LDT_{Word}	-0.044
Pretest	FA	-0.129
Pretest	DA	-0.055
Posttest	LDT_{NonW}	0.010
Posttest	LDT_{Word}	-0.014
Posttest	FA	-0.065
Posttest	DA	-0.165

Table 8.4: Correlation Matrix of PCA_{AE} with Performance on Cognitive Assessment Tasks

Independent Samples T-Test

	Welch's t	**df**	**p**	**MD**	**SE**	**Cohen's d**
LDT_{NonW}	-0.78	78	.44	-0.03	0.04	-0.17
LDT_{Word}	-1.21	76.2	.23	-0.06	0.05	-0.27
FA	-1.36	77.1	.18	-0.21	0.16	-0.31
DA	-1.65	77.3	.10	-0.47	0.28	-0.37
INT_{rate}	-0.61	77.4	.55	-0.03	0.06	-0.14

Note. H_a $\mu_{PFC} \neq \mu_{SHAM}$

Table 8.5: Group Equivalence in Pretest on INT_{rate} and LDT, FA, and DA Tasks

Estimated marginal means

Task	Mean RT	SE	LCL	UCL
DA	4.354	0.045	4.266	4.442
FA	0.548	0.039	0.472	0.624

Table 8.6: Estimated Marginal Means of Semantic Relatedness of Responses on FA and DA Task

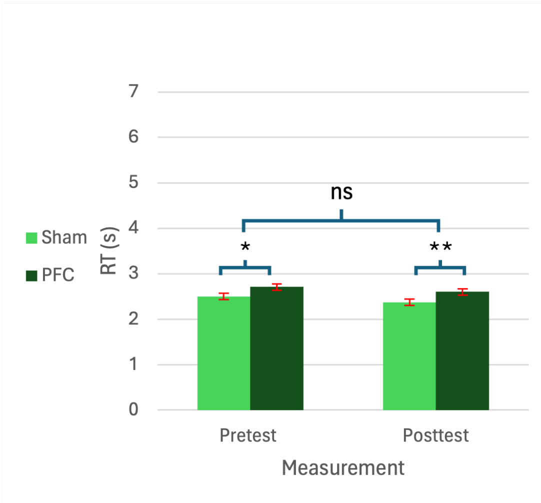
ble (Type II Wald χ^2 tests) found evidence for a substantial effect of ADT task on SR ($\chi^2(1) = 5407.5$, $p < .001$). As displayed in **Table 8.6**, we observed a difference between DA ($emm = 4.354 \pm 0.045$) and FA trails ($emm = 0.0548 \pm 0.624$) with statistically significant contrasts ($\Delta SR = 3.81 \pm 0.0518$, $z = 73.536$, $p < .001$). ADT task explained approximately 78.58% of the variability in SR ($R^2 = .79$).

8.2.2 Pretest

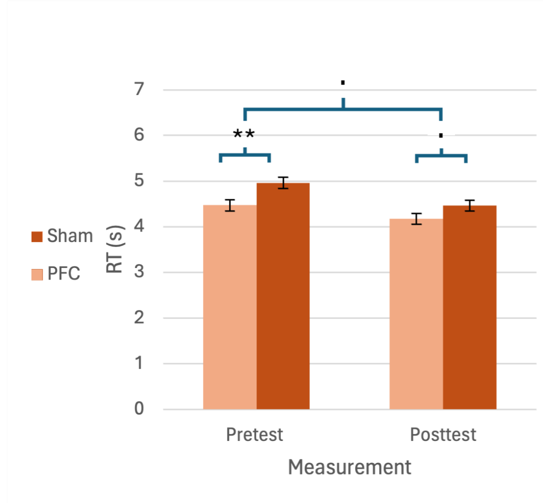
As shown in **Table 8.5**, the Independent samples t-test revealed no statistical differences between the two groups on LDT of both words (LDT_{Word}), non-words (LDT_{NonW}); and both FA and DA conditions of ADT task; and rate of intrusions (INT_{rate}) during the *Pretest*.

8.2.3 Effects of tDCS on Automatic and Controlled retrieval

The effects of ADT condition and tDCS on RT were analyzed on all 11573 correct trials using a GLMEM fit by maximum likelihood and gamma distribution (identity link function). The ANOVA Analysis of Deviance Table (Type II Wald χ^2 tests) revealed significant main effects of Measurement ($\chi^2(1) = 12.64$, $p < .001$), tDCS ($\chi^2(1) = 8.26$,



(a) The effects of tDCS on RT during FA condition



(b) The effects of tDCS on RT during DA condition

Figure 8.3: The effects of tDCS on ADT measures. Error bars represent $\pm SE$; and brackets represent the statistical significance ($^{**}p < .01$, $^{*}p < .05$, $\cdot\ p < .1$ - marginal stastical significance, ns - non-significant difference).

$p = .004$), ADT task ($\chi^2(1) = 687.857$, $p < .001$) on RTs. Interactions were observed between Measurement and Retrieval ($\chi^2(1) = 27.047$, $p < .001$), and Measurement, Retrieval and tDCS ($\chi^2(1) = 5.00$, $p = .025$). This three-way interaction indicated that stimulation of PFC interfered with the DA performance. Predictor variables collectively account for nearly 48.70% of the variability observed in RT in the task ($R^2 = .49$). As displayed in **Figure 8.3a**, contrasts between Sham and PFC groups on FA trials during the Pretest showed a statistically significant difference ($\Delta RT = -0.208 \pm 0.092$, $z = -2.259$, $p = .024$), contrasts between Sham and PFC groups on FA trials during Posttest showed a statistically significant difference ($\Delta RT = -0.228 \pm 0.088$, $z = -2.587$, $p = .009$). As shown in **Figure 8.3b**, contrasts between Sham and PFC groups on DA trials during the pretest revealed a statistically significant difference ($\Delta RT = -0.490 \pm 0.168$, $z = -2.915$, $p = .003$), contrasts between Sham and PFC groups on DA trials during the Posttest showed a marginal statistically significant difference ($\Delta RT = -0.285 \pm 0.164$, $z = -1.733$, $p = .083$).

	χ^2	**Pr**$(> \chi^2)$
Measurement	12.650	$< .001 * **$
tDCS	8.263	$.004 * *$
Retrieval	687.857	$< .001 * **$
Measurement:Retrieval	27.047	$< .001 * **$
Measurement:tDCS:Retrieval	4.991	$.025*$

Signif. codes: 0 *** 0.001 ** 0.01 * 0.05 '.' 0.1 ' ' 1

Table 8.7: ANOVA Analysis of Deviance Table: This table presents the results of the analysis of deviance for the factors Measurement, tDCS, ADT task (Retrieval)

8.2.4 Effects of EMB on Automatic and Controlled Retrieval

The effects of EMB and tDCS on RT were analyzed on all 11573 correct trials using a GLMEM fit by maximum likelihood and gamma distribution (identity link function). The ANOVA Analysis of Deviance Table (Type II Wald χ^2 tests) revealed significant main effects of Measurement ($\chi^2(1) = 14.84$, $p < .001$), tDCS ($\chi^2(1) = 8.30$, $p = .004$), ADT task ($\chi^2(1) = 689.56$, $p < .001$), and degree of grounding (EMB) ($\chi^2(1) = 49.77$, $p < .001$) on RTs. Interactions were observed between Measurement and Retrieval ($\chi^2(1) = 25.03$, $p < .001$), Retrieval and EMB ($\chi^2(1) = 68.37$, $p < .001$), and Measurement, tDCS, and Retrieval condition ($\chi^2(1) = 4.73$, $p = .030$). Predictor variables collectively account for nearly 49.08% of the variability observed in RT in the task ($R^2 = .49$). As shown in (**Table 8.9**, **Figure 8.9**) estimated marginal means indicated varied RTs across different conditions. Contrasts between RT times on FA and DA tasks with abstract stimuli showed a statistically significant difference ($\Delta RT = -1.574 \pm 0.087$, $z = -17.955$, $p < .001$). Similarly, the contrasts between RT times on FA and DA tasks with concrete stimuli showed a statistically significant difference ($\Delta RT = -2.079 \pm 0.076$, $z = -27.507$, $p < .001$). Furthermore, contrasts between RT times on FA task with concrete and abstract stimuli showed a statistically significant difference ($\Delta RT = -0.487 \pm 0.050$, $z = 9.721$, $p < .001$). On the other hand, the contrast between RT times on DA tasks with concrete and abstract stimuli revealed a non-significant difference in RT between unrelated abstract and concrete words ($\Delta RT = 0.018 \pm 0.063$, $z = 0.290$, $p = .771$), suggesting the degree of abstractness of stimuli did not affect RTs in DA trials.

	χ^2	**Pr**$(> \chi^2)$
Measurement	14.838	$< .001 ***$
tDCS	8.304	$.004 **$
Retrieval	689.557	$< .001$***
EMB	49.767	< 0.001***
Measurement:Retrieval	25.030	$< .001 ***$
Measurement:EMB	3.668	.055*
Retrieval:EMB	68.367	$< .001 ***$
Measurement:tDCS:Retrieval	4.730	.030*
Measurement:tDCS:Retrieval:EMB	1.237	.266

Signif. codes: 0 *** 0.001 ** 0.01 * 0.05 '.' 0.1 ' ' 1

Table 8.8: ANOVA Analysis of Deviance Table: This table presents the results of the analysis of deviance for the factors Measurement, tDCS, ADT task (Retrieval), and degree of grounding of stimuli (EMB)

Estimated marginal means

Task	**EMB**	**Mean**	**SE**	**LCI**	**UCI**
FA	Abstract	2.91	0.0588	2.79	3.02
DA	Abstract	4.48	0.0930	4.30	4.67
FA	Concrete	2.42	0.0451	2.33	2.51
DA	Concrete	4.50	0.0818	4.34	4.66

Results are averaged over the levels of Measurement and tDCS
Confidence level used: 0.95

Table 8.9: Mean RT on ADT Tasks based on Stimuli type

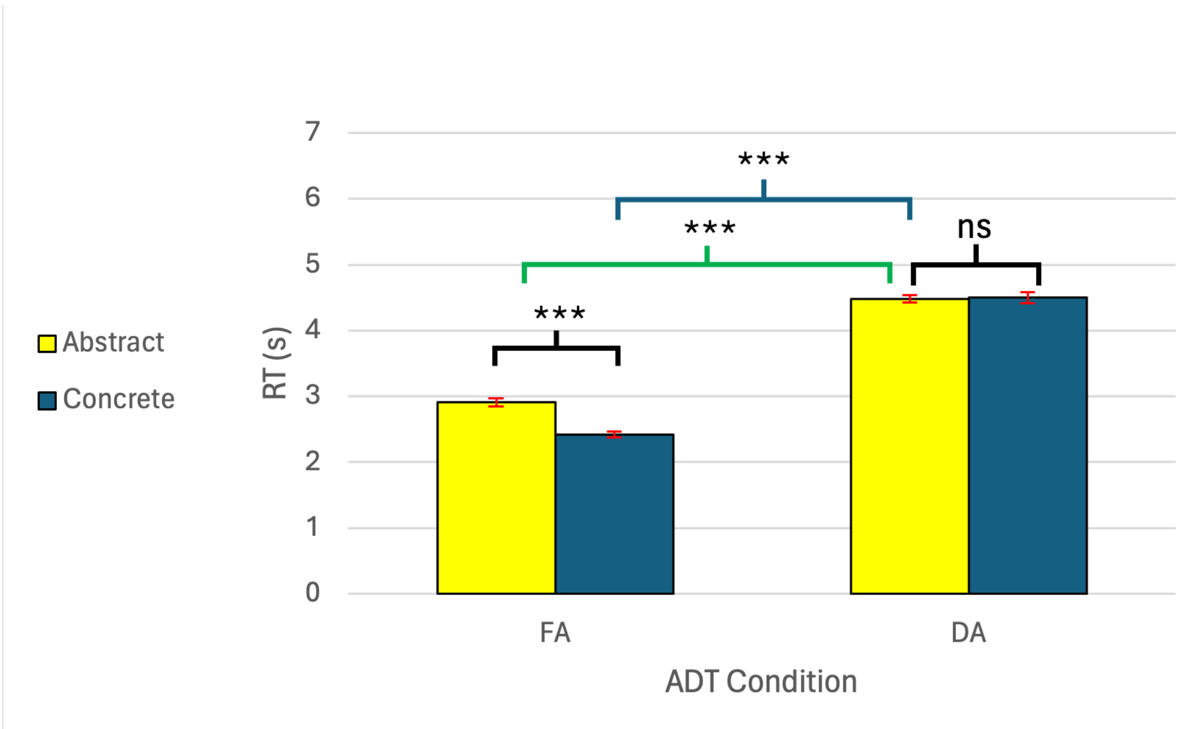


Figure 8.4: The effects of EMB on ADT measures. Error bars represent $\pm SE$; and brackets represent the statistical significance (***$p < .001$, ns - non-significant difference.)

Chapter 9

Discussion

In the present study, we set a goal of examining the role of grounding in semantic cognition. First, we developed a set of appropriate stimuli. Drawing inspiration from previous research, we collected ratings of 178 Slovak words in 7 sensorimotor features, through the means of an online questionnaire. These sensorimotor ratings enabled us to conduct an experimental study investigating the role of grounding in semantic cognition. Recent advances in the study of semantic cognition suggest that control over semantic retrieval depends on an interaction of two separated systems: the semantic control system underpinned by the pre-frontal cortex (PFC) and the semantic representation system consisting of multiple modality-specific areas interconnected via the semantic hub located in the anterior temporal lobe (ATL) (Ralph et al., 2017). To assess the effect of abstractness on semantic retrieval, the participants of the study underwent a modified version of the associative-dissociative retrieval task (ADT), designed to assess inhibitory control over semantic retrieval (Marko et al., 2024). The causal role of the left PFC was explored by transcranial direct current stimulation (tDCS) and ADT task. Finally, we investigated the role of the grounding on the effects of stimulation, to assess how the left PFC is involved in semantic processing of abstract vs concrete concepts.

9.1. Internal validity

To ensure the internal validity of the experiments, we employed several measures.

We utilized SimNibs v3.1 (Saturnino et al., 2019) to simulate the electric field intensity of the stimulation montage to verify we targeted the regions of interest. The resulting simulation confirmed the polarization of the VLPFC area with minimal influence on the regions adjacent to PFC. Furthermore, we recruited only healthy participants without a prior history of mental illnesses; and not under any influence of mind-altering substances or medication, that could affect performance on the cognitive assessments. Moreover, the experimental groups showed no significant differences in sociodemographic factors that may account for the experiment's outcomes. Finally, a double-blinded study design was chosen to minimize the placebo effect and observer bias. Debriefing sessions confirmed that neither participants nor researchers could accurately guess whether sham or verum stimulation was applied during the experimental session. Moreover, left-handedness and ambidexterity are associated with the altered functional organization of the lexical-semantic brain network compared to the right-handed population (Sha et al., 2021). Therefore participants underwent the Edinburgh Handedness Inventory - short form (Veale, 2013) and only right-handed volunteers were accepted. The subsequent analysis confirmed no significant difference between the groups on the handedness, mitigating the functional diversity of VLPFC between the experimental and control groups.

To account for cognitive differences between the groups, that could interfere with the cognitive assessment on the ADT test the participants underwent the broad general retrievability (gR) test. The analyses of the performance on the gR along with the performance on ADT and LDT during the Pretest lend support to the equivalence of cognitive abilities, between the groups, related to semantic processing. Since schizotypal personality traits have been previously associated with altered lexico-semantic processing (Kiang et al., 2010), participants underwent CAPE questionnaire (Stefanis et al., 2002; Slovak version by Forgáčová et al., 2019) used for self-reporting of psychotic-like experiences. Following analysis of the CAPE results confirmed the equivalence of the two groups, alleviating concerns about possible interference of altered semantic processing caused by schizotypal traits with the study's conclusions. Finally, despite the employment of a standardized sham tDCS protocol, the groups differed in the perception of adverse effects caused by the stimulation. Nevertheless, we employed a Principal Component Analysis (PCA) to identify a dominant factor responsible for the perception of adverse effects. The post hoc analysis excluded a dominant factor's role in performance on cognitive assessment tasks. Moreover, there was no significant difference in this factor between the groups. Therefore, it is unlikely, that differences between the groups' performance on cognitive assessment tasks could be accounted to the heightened levels of adverse effects experienced by the control group.

All in all, the experimental groups were screened thoroughly to mitigate any unintended factors that could potentially account for the outcomes of the experiment.

9.2. General evaluation of hypotheses

We successfully replicated the previous findings, showing that production of the semantically unrelated responses requires significantly more processing time, than generating free associates (Marko & Riečanský, 2021; Marko et al., 2018, 2024). In line with previous research, we argue, that additional processing time accounts for the inhibition cost resulting from interfering prepotent associates that are automatically evoked by the verbal stimuli.

The degree of sensorimotor grounding had an effect on retrieval times (RT) during the ADT task. We suggest that these outcomes support the notion that modal systems for perception and action play a role in semantic processing (Barsalou, 1999, 2008, 2009; Kemmerer, 2014; Shapiro, 2019).

Consistent with prior findings (Paivio, 2013; Vignali et al., 2023), we observed a notable decrease in RT during the automatic retrieval of concrete compared to abstract words. As predicted by hypotheses, we did not find a statistically significant effect of abstractness on the RT during controlled retrieval.

Furthermore, the outcomes support the potency of tDCS in modulating semantic cognition (Joyal & Fecteau, 2016; Pisoni et al., 2017). Contrary to the previous research (Marko & Riečanský, 2021), we observed, that the stimulation of VLPFC led to an increase in RT during the controlled retrieval (DA condition of ADT). In accordance with Marko and Riečanský (2021) and Ralph et al. (2017) we observed, that the stimulation of VLPFC did not have a significant effect on the automatic retrieval (FA condition of ADT).

Contrary to our expectations, we could not observe a significant interaction between the degree of grounding and stimulation of VLPFC on RT during the ADT task.

9.3. The Effect of Grounding on Semantic Retrieval

In line with previous evidence (Paivio, 2013; Vignali et al., 2023), we found concrete concepts require less processing time than abstract ones during the FA trials.

These observations are consistent with the GCM model, which claims that semantic processing requires re-enactment based on prior sensorimotor experience (Barsalou, 2009). Moreover, the simulation of semantic features in the given context is inherently assumed by multiple neuroimaging studies in support of GCM (Shapiro, 2019). Therefore we argue that a higher degree of sensorimotor grounding facilitates the automatic retrieval of concepts as expected by modal models of semantic cognition.

An alternative explanation for the outcomes is consistent with dual-coding theory (DCT; Paivio, 2013), which suggests no difference between abstract and concrete representations in lexical encoding. Bottini et al. (2022, as cited in Vignali et al., 2023) observed, that both blinded and sighted individuals are faster to process visual words compared to abstract words during lexical-decision tasks, suggesting the *concreteness advantage* could not originate from previous sensorimotor experiences. Moreover, Vignali et al. (2023) observed, that no brain region showed a greater activation for abstract compared to concrete features during a semantic judgment task. Furthermore, they observed greater activations for concrete semantic information only after a significant amount of time has passed after word presentation. Therefore, there is strong evidence supporting the notion that the *concreteness advantage* observed during the automatic retrieval might have not been caused by a profound grounding of concrete words in sensorimotor features.

Contrary to that, we propose a view on the outcomes of the previous and present study based on the GCM model. As articulated by Barsalou (2009), when a situation is experienced over and over, the respective simulations become rooted in the *simulators*, and the situated conceptualization becomes automatically activated during the appropriate context. We suggest that even highly visual concepts become confidently grounded in sensorimotor features acquired through senses other than sight in blind people, and previously mentioned semantic features of words (Bi, 2021). Therefore we suggest that characteristics of words, such as age of acquisition are not the cause of the experiments' outcomes, but rather facilitators of the processes by which the words acquire their meaning as proposed by GCM theories.

Conversely to the FA trials, we did not find a statistically significant effect of the degree of abstractness on the performance during the dissociation trials. Prior research suggests, that generating dissociative response requires inhibition of automatic semantic processing (Marko & Riečanský, 2021; Marko et al., 2018; Ralph et al., 2017). An explanation of this phenomenon can be offered by GCM (Kemmerer, 2014; Shapiro, 2019) which posits spontaneous brain activation of areas responsible for semantic features of concepts. Argumenting from a point of view of GCM, the DA task requires a higher inhibition tax of spontaneously activated semantic features, therefore higher levels of grounding may not facilitate the retrieval of unrelated responses. An alternative explanation would require greater inhibition of automatically evoked prepotent associations caused by factors (e.g., previously mentioned contextual availability).

9.4. The effect of tDCS on Semantic Retrieval

In contrast to the previous research (Marko & Riečanský, 2021) and the hypotheses, we observed that tDCS applied to the VLPFC interfered with RT during controlled retrieval. Similarly to Marko and Riečanský (2021), we propose, that the effect of tDCS on the retrieval latencies during the DA trail can be attributed to the left lateral PFC role in semantic control. Our outcomes bring further support to the notion that lateral PFC plays a role in the inhibition of automatically evoked associations (Badre & Wagner, 2007). Moreover, these outcomes are in line with the Controlled Semantic Cognition (CSC) model (Ralph et al., 2017), which attributes the role of semantic control partly to lateral PFC.

Contrary to the outcomes of this study, Marko and Riečanský (2021) observed, that stimulation of the left PFC led to decreases in RT during the DA condition of ADT task. As pointed out by Hassanzahraee et al. (2020) different intensities of tDCS can have a vastly different effect on neuronal excitability. What's more, even small differences in electrode positioning, the size of electrodes, or the direction of the current flow can impact the behavioral effects of the stimulation on the outcomes of the cognitive assessment (Hannah et al., 2019; Penolazzi et al., 2013). Marko and Riečanský (2021) attached two conductive electrodes ($5cm \times 7cm : 35cm^2$), with anode between F3 and AF3 and the cathode was centered between T7 and P5 of the international system of EEG electrode placement, with stimulation set to 2 mA ($0.057mA/cm^2$) and the current flowing from frontolateral to temporal regions. In the current study, the stimulation montage consisted of 3 electrodes ($3cm \times 3cm : 9cm^2$) - an anode placed between F7 and F5 and two cathodes placed on Cz and F2, with stimulation set to 2mA ($0.222mA/cm^2$). We suggest, that the opposite outcomes observed in this study can be attributed to the different intensities of the stimulation and stimulated areas stemming from differences in the stimulation montage.

Conversely, the stimulation did not impact retrieval latencies during FA trials. The outcomes lend support to the 'hub-and-spoke' theory of semantic representation (Patterson et al., 2007), which attributes the role of semantic representation to the anterior temporal lobe (ATL) serving as an integrator of information from several modality-specific areas. Furthermore, these outcomes are in line with the CSC model (Ralph et al., 2017), which proposes the activation of PFC during semantic processing occurs mainly during tasks that tax the semantic control. We propose, that the tDCS did not impact the automatic retrieval, because the generation of associated concepts requires little to no semantic control. Therefore, the stimulation of the left VLPFC - the area highly activated during inhibitory activity and semantic control in general, did not affect the retrieval latencies in

FA trials. Finally, we suggest that because of the reasons stated in the previous section, this is caused by the grounding of concepts in sensorimotor features.

9.5. Interaction between tDCS and Degree of Grounding

Multiple studies have shown higher engagement of the left PFC in the semantic processing of abstract concepts compared to the concrete ones (Wang et al., 2010). Specifically Hoffman et al. (2015) carried out an fMRI investigation, in which they observed more pronounced engagement of left PFC and ATL during the semantic judgment task. This effect was further heightened for the conditions arguably requiring a higher amount of semantic control. Moreover, the role of the PFC was further amplified for conditions that did not provide additional context. Lastly, Gnedykh et al. (2022) found that the application of tDCS to Broca's area, located in the left PFC improves the acquisition of novel abstract words.

Based on the previous results, we hypothesized that anodal stimulation of the VLPFC would lead to improvement of both automatic and controlled semantic processing and retrieval of abstract words. Contrary to our expectations, the analysis did not reveal any significant interaction between tDCS applied to VLPFC, the degree of grounding, and the ADT task on the retrieval latencies. Based on the previous observation, that the stimulation of VLPFC affects the retrieval latencies of DA trails, these results imply that left PFC does not play a more significant role in the semantic processing of abstract words compared to concrete words. These outcomes align with Vignali et al. (2023), which observed no differences in brain activations between abstract and concrete concepts during the semantic judgment task.

An alternative explanation of this outcome could be that semantic inhibition and retrieval of abstract concepts are underpinned by the same neural network involving left VLPFC, but the functionality of the network was altered by tDCS. There exists evidence supporting the explanation, that tDCS can alter computations within functional networks and enhance one process at the cost of other processes (Bikson & Rahman, 2013). Therefore, tDCS applied to the left VLPFC might have enhanced the retrieval abilities of the VLPFC at the cost of interfering with the inhibition of prepotent associations. This explanation does not contradict, that left-lateral PFC might implement both processes.

9.6. Limitations and Future Directions

The following limitations should be considered while interpreting the outcomes of this study.

The questionnaire was used to collect the degree of grounding in sensorimotor features. As a result, the abstract words were chosen based on the lack of a purpose or significance of a given sensorimotor attribute to the words' meaning. On the contrary, present-day accounts of embodied accounts, take into account the role of societal conditioning in language acquisition, partially incorporating ideas of Skinner (1957). As articulated by Reinboth and Farkaš (2022) the concepts acquire their meaning by both sensorimotor interactions with the environment and additionally by other linguistic and social processes. Diveica et al. (2024) performed exploratory factor analysis of multiple sensorimotor ratings of words in a total of 18 dimensions, which clustered the dimensions into six semantic dimensions: sub-lexical, distributional, visuotactile, body action, affective, and social interaction. Subsequent analysis of the previous studies where participants underwent lexical decision task (LDT) and semantic decision task (SDT) have revealed that socialness and affectiveness have both facilitated decision tasks of abstract words, suggesting they both play an important role during the acquisition of abstract concepts. Moreover, partially non-overlapping correlates of neural activity during imaging tasks suggest the existence of different categories of abstract concepts (Conca et al., 2021). These observations align with the low prediction accuracy of the forward-encoding model by Fernandino et al. (2016) on abstract words. Collecting sensorimotor ratings of Slovak words offers a novel and much-needed way of investigating hypotheses based on theories of Embodied Cognition with cognitive-behavioral tests on Slovak participants. Despite that, we encourage further exploration, focused on the grounding of Slovak words in the social processes, which has been mostly neglected by modal theories of cognition until very recently.

Furthermore, the effects of tDCS were simulated before the start of the experimental study, and the simulation verified that we targeted left PFC without minimal impact on neighboring regions. However, it cannot be ruled out that the observed effects were caused by factors other than the heightened excitability of neurons located in the left PFC, such as the ability of tDCS to modulate larger brain networks through the release of various neurotransmitters (Frase et al., 2021; Kronberg et al., 2017; Watanabe et al., 2023; Yamada & Sumiyoshi, 2021). As a result, additional research is needed to thoroughly understand the specific mechanism of tDCS to rule out any potential interference of these effects with the proposed outcomes.

Additionally, in the present study participants were asked to report intrusions during dissociative trials of the ADT task. Since these data were not analyzed we are unable to distinguish whether left PFC is employed during a form of retroactive (post-retrieval) inhibition, wherein inappropriate concepts concerning the current task demands are being suppressed, or a form of proactive (pre-retrieval) inhibition modulating the access to semantic knowledge in general, therefore preventing individuals from encountering memory intrusions. Further analysis is needed to determine, whether stimulation of the left VLPFC led to task-dependent changes during the controlled retrieval or if the stimulation broadly affected the semantic retrieval abilities independent of the current retrieval condition.

It has been shown, that the release of various neurotransmitters during tDCS can affect synaptic plasticity by initiating Long-term potentiation and Long-term depression (Watanabe et al., 2023). These effects are widely considered to play a crucial role in learning. In a recent study, Gnedykh et al. (2022) created a set of novel pseudo-words specifically created for the Russian language. Afterward, they set up a tDCS study, in which the participants underwent a controlled learning process of these novel concepts. Their outcomes suggest that the application of tDCS over Broca's area had a greater effect on learning novel abstract concepts compared to concrete ones, indicating that left PFC plays a direct involvement in the acquisition of abstract semantics. In the present study, we have conducted the whole experiment during one experimental session. Therefore, we cannot exclude the possibility, that the stimulation of the VLPFC had some longer-lasting changes to the structure of abstract concepts versus concrete ones, which may lead to enhancement of controlled or automatic semantic retrieval.

Finally, it is important to stress that the research sample of both the sensorimotor questionnaire and cognitive assessment experiment consisted mainly of college students and young working adults. Therefore the generalizations of the study outcomes might suffer from the sample bias. Moreover, these outcomes might not account for changes in neurological semantic cognition caused by aging.

Chapter 10

Conclusion

In the present study, we examined how sensorimotor features shape semantic cognition. First, we acquired probably the first set of sensorimotor ratings of Slovak words and successfully applied the collected data to perform a cognitive assessment study. Above all, the ratings facilitate further studies examining the nature of concepts in a variety of disciplines with applications ranging from comparative linguistic studies to explorations into neuro-correlates of semantic processing.

In the next phase, we explored the effect of sensorimotor grounding on automatic and controlled semantic cognition. We utilized the associative-dissociative retrieval task to assess the effects of grounding on semantic cognition. The outcomes of this thesis, support the broad narrative of the Grounded Cognition Model, by showing that sensorimotor features are involved in semantic processing.

Next, we tested the left PFC's causal role in the semantic cognitive process using the neuroimaging method known as transcranial direct current stimulation, or tDCS. The outcomes bring further evidence of the ability of tDCS to modify semantic cognition and accent its potential as a tool with several applications in the treatment of brain and mental disorders. By showing that anodal tDCS applied over the left PFC affects retrieval times during the generation of dissociations we gathered additional evidence, that the left PFC is causally involved in the inhibitory processes required for the proper employment of semantic knowledge. Therefore, our results fall in line with the Controlled Semantic Cognition model, which attributes the role of semantic control to the left PFC.

Contrary to our expectations, we did not observe any differences between the effect of stimulation on more abstract versus more concrete words. Additional research is therefore needed to determine, whether this was caused by the tDCS setup, the chosen cognitive task, or because the left PFC does not play a substantially more pronounced role during semantic control of abstract concepts compared to concrete ones.

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