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Comprehension of Ambiguous Idioms in Prefrontal Cortex: Evidence from rTMS

Belirsiz Deyimlerin Anlaşılmasında Prefrontal Korteksin Rolü: Bir rTMS Çalışması

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ABSTRACT

The cognitive processes related to idiom comprehension have been predominantly associated with neural mechanisms and conceptual mapping processes controlled by the dorsolateral prefrontal cortex (DLPFC). Although the role of the DLPFC in idiom comprehension has been extensively studied, ambiguous idioms—those with more than one acceptable meaning—have been relatively understudied in the neuroscientific literature. This study explores how the left and right DLPFC contribute to resolving ambiguous idioms, with a focus on understanding the neural mechanisms underlying conceptual mapping during the comprehension of such idioms. In the study, the left and right DLPFC regions of 15 native Turkish-speaking participants were temporarily inhibited using repetitive transcranial magnetic stimulation (rTMS) to examine the role of prefrontal areas in the brain in resolving ambiguous idioms. Following the brain stimulation, participants engaged in an experiment that required them to interpret both literal sentences without figurative meaning and ambiguous idiomatic expressions in which all figurative interpretations were meaningful and plausible. The findings revealed that when left DLPFC was suppressed, participants' ability to accurately comprehend the figurative meanings of ambiguous idioms was significantly impaired, as evidenced by increased reaction times and decreased accuracy rates. In contrast, no significant impairment in processing ambiguous idioms was observed when the right DLPFC was suppressed. These findings suggest that the cognitive load involved in processing ambiguous idioms with multiple acceptable meanings is predominantly managed by the left hemisphere. This study provides insight into the functions of both the right and left prefrontal areas of the brain during the resolution of ambiguous linguistic units, offering further understanding of lateralization, a key phenomenon in the neuroscientific processes of language comprehension.

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1. Introduction

1.1 Idioms, Ambiguity and Conceptual Mapping

Early definitions describe idioms as linguistic expressions composed of multiple words, where literal meanings are lost through conventionalization (Aksan, 2003, Palmer, 2001; Çotuksöken, 1998). These expressions represent a unique linguistic phenomenon where the sum of the parts does not equal the whole, making them particularly intriguing for linguists and cognitive scientists

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alike. Idioms are seen as constructions with syntactic and semantic limitations, characterized by their fixed and culturally rooted nature (Arıca-Akkök, 2007). This fixed nature often reflects deep-seated cultural norms, beliefs, and values, which can make idioms challenging to translate or understand across different languages and cultural contexts. Cognitive approaches suggest idioms are conceptualizations shaped by thought systems and world knowledge (Lakoff, 1993). These conceptualizations often involve abstract thinking and the ability to understand metaphorical language, which is a key feature of human cognition. Despite the lack of a direct link between idiomatic and literal meanings, native speakers can infer the intended meaning, which involves complex cognitive processing (Bobrow & Bell, 1973; Weinreich, 1969). This inferential process relies heavily on the listener's ability to use context effectively, drawing on both linguistic and extralinguistic cues to resolve the inherent ambiguity in idiomatic expressions. The mental lexicon, where idioms are thought to be stored as fixed semantic units, plays a crucial role in this process, allowing for the rapid retrieval of figurative meanings before literal ones are even considered (Swinney & Cutler, 1979). This idea has been supported by numerous psycholinguistic studies, which suggest that the automaticity of idiom processing is a result of their frequent usage and the strong associative links that have been formed between the idiom's form and its meaning (Gibbs 1980; Cacciari & Tabossi, 1988).

Idiom comprehension is influenced by several factors such as familiarity, frequency, predictability, and ambiguity, which directly affect how they are perceived (Cronk, Lima, and Schweigert, 1993; Giora and Fein, 1999; Titone and Connine, 1999). Familiarity, in particular, is a crucial determinant of how quickly and accurately an idiom is processed. Idioms that are highly familiar to the speaker are often processed with greater ease and speed, due to the strengthened mental representations of these expressions. Frequency of use also contributes to the robustness of these representations in the mental lexicon, making it easier for speakers to retrieve and comprehend idiomatic expressions rapidly. Predictability within a given context can further facilitate comprehension, as it allows speakers to anticipate the occurrence of an idiom and prepare for its interpretation (Cacciari et al., 2007). As opposed to the facilitative effects of these factors, ambiguity adds a layer of complexity, as idioms with multiple potential meanings require the listener to engage in more sophisticated cognitive processing to determine the intended meaning.

The ambiguity phenomenon in idioms, which is the focus of this study, refers to the situation where some idioms have two meanings simultaneously (Lodge and Leach, 1975). This duality can manifest in various forms, such as idioms that have both a literal and a figurative meaning, or idioms that have multiple figurative meanings depending on the context. For instance, the English idiom "spill the beans" can mean both "to spill the beans" literally and "to reveal a secret" figuratively, depending on the context. This duality complicates processing and requires more cognitive load for inference based on the context. The complexity of such idioms lies not only in their dual meanings but also in the cognitive effort required to navigate these meanings and arrive at the correct interpretation. Similarly, the Turkish idiom "*söz kesmek*" contains two different and possible meanings. To determine which meaning is used in a communicative setting, the listener must operate mental processes such as conceptual mapping, combining the speaker's intent with contextual information at that moment. Conceptual mapping is a cognitive process that organizes, structures, and connects ideas, concepts, and information into a network of associations. This process is essential for understanding language, particularly when it comes to figurative language, which often involves abstract and non-literal meanings (Lakoff & Johnson, 1980, Jackendoff, 1992). The relationship between idiom comprehension and conceptual mapping has been an interesting topic within cognitive linguistics and psychology. Researchers have explored how conceptual mapping enables people to comprehend and make sense of complex information by establishing mental links between various concepts (Lakoff & Johnson, 1980). When we encounter an ambiguous idiom, our cognitive system must activate and select the appropriate conceptual

mappings to accurately interpret it. This involves three key stages: (1) Contextual Activation: The context activates relevant meanings (Swinney & Cutler 1979; Tabossi & Zardon, 1993). For example, if the conversation is about sleeping, the 'go to bed' meaning of 'hit the sack' is more likely to come up. (2) Mapping Selection: Based on the context, the brain chooses the best acceptable meaning from among several options. (3) Integration: The chosen meaning is then integrated into the wider context to ensure consistent understanding (Hagoort, 2007). These stages highlight the flexibility and adaptability of the cognitive system in navigating linguistic ambiguities (Gibbs et al., 1989).

An early study by Cacciari and Glucksberg (1991) proposed that figurative expressions activate frontal regions of the brain responsible for the linguistic analysis of the expression. Especially, the language-related functions of the dorsolateral prefrontal cortex (DLPFC) encompass several elements of language processing, including discourse management, semantic integration, interpretation of the nonliteral meaning, inference making, and ambiguity resolution. These functions are critical for the successful comprehension of idiomatic expressions, which often require the integration of multiple levels of meaning. Non-invasive brain stimulation studies have revealed that stimulation of the prefrontal areas, particularly the DLPFC, clearly impaired the comprehension of idiomatic expressions (Fogliata et al., 2007). This suggests that the DLPFC is not only involved in the comprehension of literal language but is also crucial for interpreting more complex and abstract language forms, such as idioms. The DLPFC's role in managing cognitive control and executive functions further underscores its importance in processing the nuanced and context-dependent meanings of idiomatic expressions. A transcranial magnetic stimulation study by Rizzo et al. (2007) observed that after applying inhibitory repetitive transcranial magnetic stimulation (rTMS) to the dorsolateral prefrontal cortex (DLPFC), -also known as the "cognitive control region"- participants' idiom processing was impaired. This finding supports the idea that the DLPFC plays a pivotal role in managing the cognitive load associated with idiom comprehension, particularly when the idioms are ambiguous and require the integration of multiple possible meanings. Hauser et al. (2016) suggested that left ventrolateral prefrontal cortex (VLPFC) stimulation affected the processing of idioms, further indicating that different regions within the prefrontal cortex may contribute to various aspects of figurative language processing. Kurada et al. (2021) found that left DLPFC functions are more critical when referring to the figurative associations of the idioms, adding to the growing body of evidence that highlights the importance of this brain region in the nuanced interpretation of language. Behavioral and imaging studies have also demonstrated that the right hemisphere (RH) plays a role in resolving semantic ambiguity and understanding the figurative aspects of language (Anaki et al., 1998; Brownell et al., 1990, Bottini et al., 1994; Faust & Chiarello, 1998; Mashal et al., 2005, 2007; Pobric et al., 2008; Eviatar & Just 2006). Giora (2005) claimed that the right hemisphere is involved in processing non-salient interpretations and has a special role in ambiguity resolution. An fMRI study (Mashal et al., 2008) suggested that RH areas are involved in semantic ambiguity resolution and in processing non-salient meanings of conventional idiomatic expressions. According to Beeman (1998) and Jung-Beeman (2005), both hemispheres are engaged in semantic activation, integration, and selection of meaning when processing figurative language; however, the right hemisphere (RH) is more tuned to establishing relationships between weak and dispersed semantic information, organizing pragmatic information, and reinterpreting language stimuli (Beeman, 1998; Beeman & Chiarello, 1998; Jung-Beeman, 2005). These findings suggest that while the left hemisphere, particularly the DLPFC, is involved in the more structured and direct aspects of language processing, the right hemisphere contributes to the broader and more integrative aspects of meaning construction.

Based on these controversial findings in the literature, this study sought to examine the role of the dorsolateral prefrontal cortex (DLPFC) in the comprehension of ambiguous idioms, which requires

complex conceptual mapping. Specifically, we aimed to investigate how the temporary suppression of activity in both the right and left DLPFC, using repetitive transcranial magnetic stimulation (rTMS), affects the processing of ambiguous idioms. Through this approach, we aimed to elucidate the contribution of each hemisphere's DLPFC to the cognitive mechanisms underlying idiomatic language comprehension. By examining the effects of TMS on each hemisphere, we sought to determine if the suppression would primarily affect the processing of the literal or the idiomatic interpretation of the ambiguous expressions.

This research contributes to our understanding of how different regions of the brain are involved in the complex task of language processing and highlights the importance of the DLPFC in managing the cognitive processes required for interpreting ambiguous idioms, especially in contexts where both literal and figurative meanings coexist. By investigating the effects of TMS on the right and left DLPFC, this study aims to shed light on the specific roles these brain regions play in the comprehension of idiomatic expressions, offering a deeper insight into the lateralization of language functions in the human brain.

2. Method

2.1 Participants

The study included 15 right-handed volunteers (9 males, 6 females, age range: 18-24 years, mean age: 21.04, SD: 0.71) who were monolingual native Turkish speakers, university students, and had no neurological or psychological health issues. Right-handedness was controlled to account for potential hemispheric dominance effects on language processing (Nalçacı, Kalaycıoğlu, Güneş & Çiçek, 2002). Participants were screened for contraindications to rTMS application, following Wassermann's (1998) guidelines, including a detailed medical history to ensure no epilepsy, history of seizures, or implanted medical devices were present. Strict inclusion criteria ensured all participants had no history of language, speech, hearing impairments, or psychiatric/neurological diseases like epilepsy, depression, or anxiety. A pre-screening questionnaire covered health and lifestyle factors that might influence study outcomes or pose risks during rTMS sessions. Participants were informed about the nature of the study, including the rTMS procedure, the tasks they would be required to perform, and the potential risks involved. All participants provided informed consent prior to their involvement in the study, in accordance with the ethical standards outlined in the Declaration of Helsinki. The study was approved by the Ethics Committee of Ankara University, ensuring that all procedures adhered to ethical guidelines for research involving human subjects. Participants were compensated for their time and effort with a small monetary reward, and they were debriefed at the end of the study regarding the aims and expected outcomes of the research.

2.2 Experimental Stimuli

The study's experimental stimuli comprised three categories: (1) ambiguous idioms, (2) literal expressions, and (3) filler items. To ensure the robustness of the stimuli, a comprehensive screening process was employed. A total of 11,216 idioms were initially sourced from the Turkish Language Association's Current Turkish Idioms Dictionary (April, 2009). After a rigorous selection process involving a panel of expert linguists to confirm the ambiguity of idioms that could be interpreted in both a literal and figurative sense, 10 idioms in the form [EÖ AÖ E] (subject-object-verb order) with two words in basic word order were selected. These idioms, such as "söz kesmek," (*to interrupt* or *getting engaged*) were chosen due to their dual interpretative potential. For the control sentences, 10 literal expressions were selected, ensuring that they had no figurative meaning and matched the idioms in syntactic structure ([EÖ AÖ E]) regarding the word order. The selection of these literal sentences aimed to maintain structural consistency with the idioms, allowing for a direct comparison between literal and figurative processing. In addition, three target

words were meticulously matched with each stimulus to further test comprehension and reaction times. For instance, for the idiom "söz kesmek," two related target words e.g., "nişan" (engagement) and "kabalık" (rudeness) and one unrelated target word e.g., "silgi" (eraser) were selected. These target words were carefully chosen and compared for frequency using the Turkish National Corpus (TNC, Aksan et al., 2016) to ensure that they were appropriately matched in terms of usage frequency, thus controlling for any potential confounding variables related to word familiarity or frequency effects.

To create a balanced experimental design and prevent participants from adopting any specific strategies during the task, an additional set of 20 idioms was included as filler items. These fillers were carefully selected to maintain numerical balance between the experimental conditions, ensuring that the participants remained engaged and that their responses were not biased towards any particular category of stimuli. Moreover, all experimental stimuli were meticulously matched for psycholinguistic properties, such as sentence length (idioms: M = 2.06, SD = 1.34; literal sentences: M = 2.11, SD = 1.31), predictability (idioms: M = 4.25, SD = 3.34; literal sentences: M = 4.31, SD = 3.41), and familiarity (idioms: M = 4.29, SD = 3.24; literal sentences: M = 4.33, SD = 3.30). These matching procedures were critical in ensuring that any differences in processing were attributable to the ambiguity and idiomatic nature of the expressions rather than other linguistic factors. Finally, all the experimental stimuli were digitized and transferred into a computer environment using the SuperLab.5 stimulus presentation software. This software was specifically chosen for its ability to precisely measure reaction times and accuracy, allowing for detailed analysis of the participants' responses. An evaluation experiment was then created, which provided a controlled setting to test the impact of DLPFC suppression on the comprehension of ambiguous idioms, with a focus on both literal and figurative interpretations.

2.3 Procedure

2.3.1 Brain Stimulation with rTMS

The study employed a standard inhibitory repetitive transcranial magnetic stimulation (rTMS) protocol that adhered to established TMS safety guidelines (Wassermann, 1998). This protocol was selected to ensure both the effectiveness and safety of the brain stimulation procedures. Participants underwent brain stimulation and subsequent judgment experiments across three separate sessions, designed to target the right DLPFC, the left DLPFC, and a control condition without brain stimulation (no TMS session). This within-subject design allowed for a direct comparison of the effects of rTMS on idiomatic comprehension, isolating the role of each hemisphere's DLPFC in processing ambiguous idioms. The rTMS was delivered using a MagLite magnetic stimulation device equipped with a figure-8 TMS coil. Each wing of the coil had an outer diameter of approximately 95 mm, capable of producing a peak magnetic field of around 1.5 Tesla. The figure-8 coil configuration is commonly used in TMS research due to its ability to focus the magnetic field on a specific brain region, enhancing the precision of cortical stimulation. To accurately target the dorsolateral prefrontal cortex (DLPFC) in both the right and left hemispheres, coil placement on the skull was determined using the internationally recognized EEG 10-20 system. Specifically, the coil was positioned over the areas corresponding to F3 (left DLPFC) and F4 (right DLPFC), which are standard locations for stimulating the DLPFC. The Beam/F3 Method was employed to identify these locations (Beam et al., 2009). This method involves measuring the surface distances between the nasion (the midpoint between the eyes), the inion (the prominent point at the lower rear of the skull), and the tragus (the small, pointed eminence of the external ear). These measurements provide a reliable and reproducible way to locate the DLPFC for experimental purposes. The Beam/F3 Method has been extensively validated in the literature, with studies demonstrating that it is as effective as more sophisticated neuronavigation techniques, such as MRI-guided neuronavigation, in localizing the DLPFC (Mir-Moghtadaei et al.,

2015). This validation underscores the method's utility in experimental settings where access to neuronavigation may be limited or impractical.

Before beginning the rTMS procedures, participants were thoroughly assessed for any contraindications to TMS, such as a history of seizures, metal implants in the head, or other relevant medical conditions. This step was crucial to ensure participant safety and to minimize the risk of adverse effects during the stimulation sessions. During the rTMS sessions, participants were positioned comfortably on a stretcher with their heads securely stabilized to prevent movement, which could affect the precision of the stimulation. The rTMS was then applied to the DLPFC location identified by the Beam/F3 Method, at a strength of 10% above the individual's active motor threshold (AMT) at that moment (i.e., 110% of AMT). The stimulation was delivered at a frequency of 1 Hz for a total duration of 15 minutes, amounting to 900 stimulations per session. This specific protocol is known to induce temporary suppression of cognitive functions associated with the stimulated brain region, effectively creating a temporary "virtual lesion" that allows researchers to study the impact of reduced DLPFC activity on task performance. The neuromodulatory effects of this 15-minute inhibitory rTMS protocol are known to last approximately 30 to 40 minutes, providing a window during which the cognitive functions mediated by the DLPFC are suppressed. This time frame was utilized to conduct the subsequent judgment experiments, ensuring that the effects of the rTMS were active during the critical period of idiom comprehension. Importantly, participants reported no side effects during or after the rTMS stimulation, indicating that the protocol was well-tolerated and that the safety procedures were effective. To further safeguard participant well-being and to avoid carryover effects, brain stimulation sessions were spaced at least one week apart. Additionally, the order of the sessions (right DLPFC, left DLPFC, and noTMS) was randomized for each participant, reducing the potential for order effects and enhancing the validity of the findings.

2.3.2 Experimental Task Procedure

Immediately after the inhibitory brain stimulation to the DLPFC using rTMS, participants underwent the idiom judgment experiment. This experiment was designed to measure processing efficiency and reaction times in milliseconds, providing insights into the cognitive impact of DLPFC suppression on ambiguous idiom comprehension. The entire experiment was conducted in a controlled computer environment using the SuperLab.5 stimulus presentation software, paired with a response key system to accurately capture participants' reactions. Before the main experiment began, participants completed a practice session involving five stimuli to familiarize themselves with the procedure and ensure they understood the task. This practice session was crucial for minimizing any learning effects during the actual experiment and ensuring that participants were comfortable with the task demands.

The experimental procedure started with the presentation of a fixation cross (“+”) on the screen, which was displayed for 500 milliseconds. This served as a trigger for participants to prepare for the upcoming stimulus. Following this, an idiom sentence, such as "*söz kesmek*," (to interrupt) was displayed for 2000 milliseconds. This duration was chosen to allow participants enough time to read and process the idiom without overwhelming their cognitive resources. After the idiom disappeared, a second fixation point appeared on the screen for 750 milliseconds, serving as a brief interlude before the target word was presented. The target word, which reflected either the first or second meaning of the idiom or was entirely unrelated, was then displayed for a very short duration of 250 milliseconds. This brief presentation aimed to simulate natural reading conditions and to test the immediacy of the participants' semantic processing. Following the target word, a question mark appeared on the screen, indicating that participants had 2000 milliseconds to respond. At this stage, they were asked to press the blue button if they perceived a semantic relationship between the idiom and the target word, or the red button if they did not detect any

semantic relationship. This response mechanism was designed to probe participants' ability to access and identify all possible meanings of the idiom under the influence of DLPFC suppression. To ensure the validity and reliability of the experiment, the types of stimuli—including literal sentences, idioms, and filler items—were presented in a mixed order. This randomized presentation was crucial for preventing participants from predicting the type of stimulus and developing response strategies, which could potentially bias the results. This randomization was applied not only within each session but also across the rTMS sessions themselves, ensuring that any potential order effects were minimized. Thus, the order of experimental conditions (right and left DLPFC stimulation) was also presented in a mixed order for each session.

Reaction times and accuracy values for each stimulus were automatically recorded by the SuperLab.5 software, ensuring precise and unbiased data collection. The experiment was conducted in a soundproof room, different from where the rTMS applications were performed, to eliminate any potential auditory distractions that could interfere with the participants' concentration. Participants completed the experiment alone, further ensuring that their responses were not influenced by external factors. The entire semantic judgment experiment lasted approximately 15 minutes, which was sufficient to gather the necessary data without causing fatigue or loss of focus among the participants. The experiment was conducted on a 16.5-inch monitor with a 60 Hz refresh rate, providing clear and consistent visual stimuli. Prior to starting the experiment, the distance between the participants and the screen was carefully measured and set at 60 cm to standardize the viewing conditions and ensure consistency across all sessions. This approach allowed for a comprehensive examination of the effects of DLPFC suppression on idiom comprehension, with each participant serving as their own control across different conditions.

3. Data Analysis

The data were analyzed using linear mixed-effects models created with the lme4 package (version 1.1-23) in R (R Core Team, 2013; Bates et al., 2015). The lmer() function was used for reaction time analysis, and the glmer() function for accuracy data analysis. For reaction time analysis, fixation times less than two and a half times the difference from the mean ($\mu i - (\sigma i \times 2.5)$) and more than two and a half times the sum of the mean stabilization times and standard deviation ($\mu i + (\sigma i \times 2.5)$ were excluded from the analysis. Outlier exclusion resulted in a 4% data loss. Additionally, filler items and practice session data were excluded at this stage. The primary dependent variables in this study were reaction time and accuracy. Reaction time data provided insights into how quickly participants could process and respond to the stimuli, reflecting the efficiency of cognitive processing under different experimental conditions. Accuracy data, on the other hand, offered information about the correctness of participants' responses, shedding light on their ability to comprehend and correctly interpret the ambiguous idioms presented to them. By analyzing both reaction time and accuracy, the study aimed to capture a comprehensive picture of the cognitive processes involved in idiom comprehension, particularly under the influence of DLPFC suppression. These analytical approaches ensured that the study's findings were based on robust and reliable data, allowing for meaningful interpretations and conclusions to be drawn about the effects of rTMS on idiomatic language processing.

4. Results

Initially, we compared reaction time and accuracy data across the different experimental sessions. The accuracy analysis revealed a notable decrease in accuracy when rTMS was applied to the left DLPFC, compared to the session targeting the right DLPFC (Left DLPFC: M = 0.792, SD = 0.406; Right DLPFC: M = 0.808, SD = 0.394). Additionally, the control session, where no rTMS was administered, showed a significantly higher accuracy rate than both stimulation conditions (No_TMS: M = 0.883, SD = 0.322). However, it is important to note that the difference in accuracy

rates was statistically significant only between the control session and the left DLPFC session ($p < 0.05$), indicating a specific effect related to the left hemisphere stimulation. However, the difference in accuracy rates was statistically significant only between the control session and the left DLPFC session ($p < 0.05$, Cohen's $d = 0.55$), indicating a specific effect related to the left hemisphere stimulation.

Significant findings were also observed in reaction times. Reaction times during the left DLPFC session were notably longer compared to the right DLPFC session (Left DLPFC: $M = 666.333$ ms, $SD = 351.033$; Right DLPFC: $M = 572.242$ ms, $SD = 306.732$). Moreover, reaction times in the control session, where no rTMS was applied, were significantly shorter than in both stimulation conditions (No TMS: $M = 503.975$ ms, $SD = 264.226$). Statistical analyses further confirmed that the difference between the No TMS condition and both stimulation conditions was significant ($p < 0.05$, Cohen's $d = 0.62$). The linear mixed-effects models (lme4 package in R) incorporated random intercepts for participants and fixed effects for condition. The models confirmed a significant main effect of condition on both accuracy and reaction times ($\beta = 0.45$, $SE = 0.12$, $t = 3.75$, $p < 0.001$ for accuracy; $\beta = 0.37$, $SE = 0.10$, $t = 3.40$, $p = 0.001$ for reaction times).

When analyzing the effects of brain stimulation on different types of stimuli, we found that the reaction time for ambiguous idioms was significantly longer than for literal expressions in the left DLPFC session, with this difference reaching statistical significance ($F(1, 58) = 15.67$, $p < 0.001$). Similarly, accuracy rates for ambiguous idioms were lower than for literal expressions in the left DLPFC session, with this difference also being statistically significant ($F(1, 58) = 20.89$, $p < 0.001$). These findings suggest that left DLPFC stimulation particularly affects the processing of ambiguous idioms, likely due to the increased cognitive demands associated with resolving their dual meanings. In contrast, no significant difference in reaction times or accuracy rates between literal and ambiguous idioms was observed during the right DLPFC session ($p > 0.05$), indicating that the right DLPFC may not play as crucial a role in this specific aspect of idiom processing.

Finally, when examining the effects of brain stimulation on the processing of multiple semantic references within idioms, it was observed that reaction times for the figurative meanings of ambiguous idioms in the left DLPFC session were significantly longer than for their literal meanings, with this difference being statistically significant ($F(1, 58) = 18.34$, $p < 0.001$). Similarly, the accuracy rates for correctly matching idioms with their figurative meanings in the left DLPFC session were lower than for their literal meanings, with this difference again reaching statistical significance ($F(1, 58) = 22.76$, $p < 0.001$). These findings underscore the critical role of the left DLPFC in the retrieval and processing of figurative meanings of idioms. Interestingly, in the right DLPFC session, no significant difference in reaction time or accuracy rate was found between the figurative and literal meanings of ambiguous idioms ($p > 0.05$), suggesting that the right DLPFC may not be as involved in these specific retrieval processes.

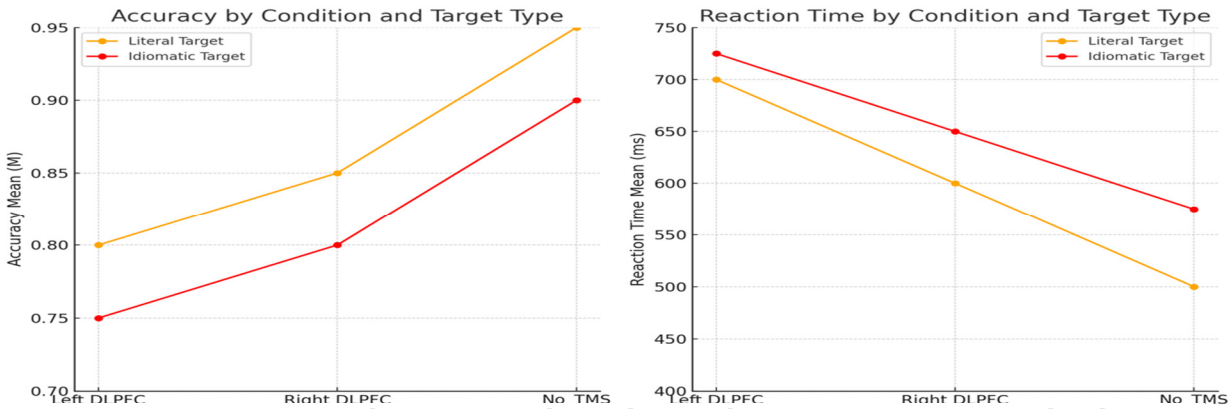

Figure 1. Accuracy and Reaction Time by Condition and Target Type in Experimental Task

Figure 1 summarizes the accuracy and reaction time for both literal and idiomatic target words across different conditions (Left DLPFC, Right DLPFC, and No TMS). The results indicate that left DLPFC stimulation notably decreased, accuracy and increased reaction times, particularly for idiomatic meanings. In contrast, the No TMS condition showed the highest accuracy and the shortest reaction times, highlighting the critical role of the left DLPFC in the retrieval of figurative meanings in idiom comprehension.

5. Discussion

In this study, we investigated the effects of repetitive transcranial magnetic stimulation (rTMS) on the dorsolateral prefrontal cortex (DLPFC), specifically focusing on how this brain region influences the processing of ambiguous idioms. By temporarily suppressing activity in the left and right DLPFC, we aimed to understand the contributions of these areas to the cognitive mechanisms involved in idiomatic language comprehension, particularly in resolving ambiguity between literal and figurative meanings. Our findings revealed that the left DLPFC plays a crucial role in the retrieval and processing of figurative meanings in ambiguous idioms. When rTMS was applied to the left DLPFC, participants showed significantly longer reaction times and lower accuracy rates when interpreting figurative meanings, compared to literal meanings. This suggests that the left DLPFC is particularly involved in the conceptual mapping processes that are necessary to resolve the ambiguity in idiomatic expressions.

These results align with the findings of earlier studies that have emphasized the importance of the DLPFC in language processing, particularly in tasks requiring the interpretation of figurative language (Rizzo et al., 2007; Fogliata et al., 2007; Kurada et al., 2021). For instance, Rizzo et al. (2007) observed that rTMS applied to the DLPFC impaired participants' ability to process idiomatic expressions, reinforcing the idea that this region is integral to managing the complexities of figurative language. Our study extends this understanding by highlighting the specific role of the left DLPFC in managing the ambiguity inherent in idiomatic expressions.

The conceptual mapping process, which is crucial for interpreting ambiguous idioms, is thought to be heavily reliant on the prefrontal cortex, particularly the DLPFC. Cognitive theories, such as those proposed by Lakoff and Johnson (1980), suggest that idioms are conceptualizations shaped by thought systems and world knowledge, rather than mere linguistic expressions. Our findings support this view, as the suppression of the left DLPFC, which is deeply involved in executive functions and conceptual mapping, led to significant difficulties in processing figurative meanings. This aligns with the research by Cacciari & Glucksberg (1991), who demonstrated the critical role of the prefrontal cortex in the linguistic analysis of figurative expressions. Furthermore, the findings from our study are consistent with those of Swinney and Cutler (1979), who argued that idioms are stored as fixed semantic units in the mental lexicon, with figurative meanings being accessed more readily than literal ones. The impairment observed in the figurative meaning processing during the left DLPFC session suggests that this area may be crucial for accessing and integrating these fixed semantic representations.

Role of Conceptual Mapping in Ambiguous Idiom Processing

The cognitive process of conceptual mapping is central to resolving the ambiguity in idiomatic expressions. When faced with an ambiguous idiom, the brain must activate and select from multiple potential mappings based on contextual information. This process is particularly demanding in idioms where both literal and figurative meanings are plausible, as it requires the integration of context with stored semantic knowledge to arrive at the intended meaning. Our results suggest that the left DLPFC is essential for facilitating these conceptual mapping processes, especially when the task involves retrieving and integrating figurative meanings. The significant impact of left DLPFC suppression on both reaction times and accuracy rates indicates that this

brain region is heavily involved in managing the cognitive load associated with resolving idiom ambiguity. Interestingly, no significant differences were found between the processing of figurative and literal meanings in the right DLPFC session. This finding suggests that while the right DLPFC contributes to language processing, its role may be more generalized or related to broader aspects of language comprehension, such as semantic integration or the resolution of more subtle ambiguities. This is in line with the work of Beeman (1998) and Jung-Beeman (2005), who proposed that the right hemisphere is more involved in processing non-salient interpretations and establishing connections between dispersed semantic information.

Implications for Idiom Comprehension and Brain Lateralization

The results of this study have important implications for our understanding of idiom comprehension and the lateralization of language functions in the brain. The distinct roles of the left and right DLPFCs in processing ambiguous idioms highlight the lateralized nature of language processing. While the left DLPFC appears to be specialized for tasks involving the retrieval of figurative meanings and conceptual mapping, the right DLPFC may play a more supportive role in handling broader semantic and integrative functions. These findings also contribute to the ongoing debate in the literature regarding the lateralization of language functions. Previous research has shown that the right hemisphere plays a role in resolving semantic ambiguity and understanding the figurative aspects of language (Anaki et al., 1998; Brownell et al., 1990; Bottini et al., 1994). However, our study suggests that the left DLPFC is more critically involved when the task demands the resolution of idiom ambiguity through conceptual mapping, particularly in accessing and integrating figurative meanings. The results also suggest that idiom comprehension, particularly when dealing with ambiguous idioms, requires a complex interplay of cognitive processes that are distributed across both hemispheres but are differentially engaged depending on the specific demands of the task. The left DLPFC's role in managing the retrieval of figurative meanings, as demonstrated by the significant impairment observed when this area was suppressed, highlights the importance of this region in the overall process of idiom comprehension.

6. Conclusion

In conclusion, this study provides robust evidence for the critical role of the left DLPFC in the processing of ambiguous idioms, particularly in tasks that require the retrieval of figurative meanings through conceptual mapping. The findings contribute to our understanding of the neural mechanisms underlying idiom comprehension and offer new insights into the lateralization of language functions in the brain. Future research should continue to explore the specific contributions of the left and right DLPFCs to different aspects of language processing, with a particular focus on how these regions interact during the comprehension of complex and ambiguous linguistic expressions. Overall, our study highlights the crucial role of the left DLPFC in the cognitive processing of idiomatic language, particularly in tasks involving the retrieval of figurative meanings. The differential effects observed between the left and right DLPFC sessions provide important insights into the lateralized functions of the prefrontal cortex in language comprehension, particularly, in understanding idioms.

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