

Cortical Organization of Action and Object Naming in Turkish: A Transcranial Magnetic Stimulation Study

Türkçede Eylem ve Nesne Adlandırmanın Kortikal Organizasyonu: Transkraniyal Manyetik Uyarım Çalışması

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ABSTRACT

It is controversial whether the linguistic distinction between nouns and verbs is reflected in the cortical organization of the lexicon. Neuropsychological studies of aphasia and neuroimaging studies have associated the left prefrontal cortex, particularly Broca's area, with verbs/actions, and the left posterior temporal cortex, particularly Wernicke's area, with nouns/objects. However, more recent research has revealed that evidence for this distinction is inconsistent. Against this background, the present study employed low-frequency repetitive transcranial magnetic stimulation (rTMS) to investigate the dissociation of action and object naming in Broca's and Wernicke's areas in Turkish. Thirty-six healthy adult participants took part in the study. In two experiments, low-frequency (1 Hz) inhibitory rTMS was administered at 100% of motor threshold for 10 minutes to suppress the activity of the left prefrontal cortex spanning Broca's area or the left posterior temporal cortex spanning Wernicke's area. A picture naming task involving objects and actions was employed before and after the stimulation sessions to examine any pre- to post-stimulation changes in naming latencies. Linear mixed models that included various psycholinguistic covariates including frequency, visual and conceptual complexity, age of acquisition, name agreement and word length were fitted to the data. The findings showed that conceptual complexity, age of acquisition of the target word and name agreement had a significant effect on naming latencies, which was consistent across both experiments. Critically, the findings significantly associated Broca's area, but not Wernicke's area, in the distinction between naming objects and actions. Suppression of Broca's area led to a significant and robust increase in naming latencies (or slowdown) for objects and a marginally significant, but not robust, reduction in naming latencies (or speedup) for actions. The findings suggest that actions and objects in Turkish can be dissociated in Broca's area.

Keywords: Nouns, verbs, object naming, action naming, Broca's area, Wernicke's area

ÖZ

Adlar ve eylemler arasındaki dilbilimsel ayrımın zihinsel sözlüğün kortikal temsilinde de geçerli olup olmadığı tartışma konusudur. Afaziye ilişkin nöropsikolojik araştırmalar ve nörogörüntüleme çalışmaları sol prefrontal korteksi, özellikle Broca alanını eylem/hareket belirten sözcüklerle ve sol posterior temporal korteksi, özellikle Wernicke alanını adlar/nesnelere ile ilişkilendirmiştir. Bununla birlikte yakın zamanda gerçekleştirilen çalışmalar, bu ayrıma ilişkin kanıtlarının tutarsız olduğunu ortaya koymuştur. Mevcut çalışma Türkçede Broca ve Wernicke alanlarının nesne ve eylemlerin işlenmesindeki rolünü araştırmak amacıyla düşük frekanslı tekrarlayan transkraniyal manyetik uyarım (tTMU) yöntemi kullanılarak gerçekleştirilmiştir. Çalışmaya otuz altı sağlıklı

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yetişkin katılmıştır. Gerçekleştirilen iki deneyde Broca alanını içeren sol prefrontal korteks veya Wernicke alanını içeren sol posterior temporal korteks aktivitesini baskılamak amacıyla düşük frekanslı (1 Hz) inhibitör tTMU motor eşğin %100'ü şiddetinde ve 10 dakika süreyle uygulanmıştır. Nesnelere ve eylemleri içeren resim adlandırma görevi kullanılarak uyandırma öncesi ve sonrası adlandırma gecikmesindeki (latansındaki) değişiklik incelenmiştir. Adlandırma gecikmesi, resmin ekrana gelmesinden itibaren katılımcının resme karşılık olarak bir sözcük üretmeye başladığı zamana kadar geçen süre olarak hesaplanmıştır. Verilerin analizinde sabit etkiler olarak sıklık, görsel ve kavramsal karmaşıklık, edinim yaşı, adlandırma uyumu ve sözcük uzunluğu dahil olmak üzere çeşitli psikodilbilimsel değişkenleri ve rastgele etkiler olarak da katılımcılar ve uyarıları içeren doğrusal karışık etki modelleri kullanılmıştır. Bulgular, kavramsal karmaşıklık, hedef sözcüğün edinim yaşı ve adlandırma uyumunun adlandırma gecikmesi üzerinde anlamlı bir etkiye sahip olduğunu göstermiştir. Ayrıca bulgular, nesne ve eylem adlandırma ayrımının Broca alanıyla ilişkili olduğunu, Wernicke alanının ise böyle bir ayrım sergilemediğini göstermiştir. Broca alanının baskılanması, nesnelere adlandırılmasında anlamlı bir yavaşlamaya, eylemlerin adlandırılmasında ise marjinal olarak anlamlı bir hızlanmaya neden olmuştur. Bulgular, Türkçede eylem ve nesnelere Broca alanında ayrıştığına, Wernicke alanında ise böyle bir ayrışma olmadığına işaret etmektedir.

Anahtar Kelimeler: Adlar, eylemler, nesne adlandırma, eylem adlandırma, Broca alanı, Wernicke alanı

Languages distinguish between different grammatical categories, particularly between nouns/objects and verbs/actions. Neuropsychological, neuroimaging, and neurostimulation research has tested whether this linguistic distinction is an organizational principle of the lexicon in the brain. For instance, early neuropsychology research associated Broca's aphasia with difficulties in processing verbs and Wernicke's aphasia with difficulties in processing nouns (Breedin et al., 1998; Caramazza & Hillis, 1991; Damasio & Tranel, 1993; Goodglass et al., 1966; McCarthy & Warrington, 1985). These observations associated the left prefrontal cortex, including the inferior frontal gyrus, with verbs and the left temporal cortex, including the posterior superior temporal gyrus, with nouns. However, later neuropsychological research has challenged these early findings (Crepaldi et al., 2011; Mätzig et al., 2009; Vigliocco et al., 2011). Neuroimaging studies employing functional magnetic resonance imaging (fMRI), among other techniques, have also produced inconsistent findings regarding the cortical separation of nouns and verbs (Crepaldi et al., 2011, 2013; Faroqi-Shah et al., 2018; Vigliocco et al., 2011). Noninvasive neurostimulation techniques, including repetitive transcranial magnetic stimulation (rTMS), have also been utilized, to a limited extent, to investigate cortical organization of nouns and verbs. For instance, inhibitory stimulation of the left prefrontal cortex associated this area with verb production but not with noun production (Cappelletti et al., 2008; Shapiro et al., 2001).

As briefly summarized above, a sizeable body of neuropsychological and neuroimaging research has examined the cortical organization of nouns/objects and verbs/actions in clinical and healthy populations, respectively. However, a relatively limited number of studies have used rTMS to address the causal relationship between cortical targets and representation of nouns and verbs in healthy populations. Even less research has examined the causal involvement of both Broca's and Wernicke's areas in processing nouns and verbs within the same study or participant group. Moreover, to our knowledge, rTMS has not been employed to address this question in Turkish, a language that is typologically different from previously investigated languages such as English and Italian. Against this background, the present rTMS study examines the dissociation of actions and objects in the left prefrontal cortex spanning Broca's area (Experiment 1) and the left posterior temporal cortex spanning Wernicke's area (Experiment 2) within the same participants. Thus, the present study aims to contribute to the debate on the cortical dissociation of nouns and verbs by utilizing rTMS with a naming task in a less studied language, Turkish, and by examining two cortical targets in a within-subjects design. In the following sections, we review evidence for cortical organization of nouns/objects and verbs/actions from different disciplines/techniques of neuroscience; that is neuropsychology, neuroimaging and neurostimulation, and then introduce our study.

Evidence from Neuropsychology

Neuropsychological research has long examined the purported dissociation between nouns and verbs. In particular, early research on aphasia suggested that individuals with nonfluent aphasia, especially Broca's aphasia, experienced greater difficulty with verbs (e.g., when naming actions) than with nouns (e.g., when naming objects), while the reverse pattern was sometimes reported for fluent aphasia, especially Wernicke's aphasia (Breedin et al., 1998; Caramazza & Hillis, 1991; Damasio & Tranel, 1993; Goodglass et al., 1966;

McCarthy & Warrington, 1985). In addition to English, this double dissociation was reported in other typologically different languages, including Italian (Piras & Marangolo, 2007) and Turkish (Ulusoy & Kuruoğlu, 2013). These findings were interpreted as greater involvement of prefrontal regions with verbs/actions and temporal regions with nouns/objects. Later research and reappraisal of previous neuropsychological studies, however, highlighted inconsistencies across studies and suggested that at least some of the observed differences between nouns and verbs could be due to confounds, such as greater processing demands associated with verbs/actions than nouns/objects, rather than linguistic distinctions per se (Crepaldi et al., 2011; Mätzig et al., 2009; Vigliocco et al., 2011).

Evidence from Neuroimaging

The extensive body of neuropsychological literature suggesting differences in cortical organization of nouns and verbs catalyzed neuroimaging studies particularly employing fMRI in healthy populations (for reviews see Crepaldi et al., 2011; Vigliocco et al., 2011; for meta-analyses see Crepaldi et al., 2013; Faroqi-Shah et al., 2018). This line of research also produced conflicting results. For instance, a recent activation likelihood estimation meta-analysis of previous fMRI and PET studies on verb and noun processing revealed distinctions, but also commonalities in the organization of nouns and verbs in the brain (Faroqi-Shah et al., 2018). In particular, verbs were associated with a left inferior frontal and bilateral middle temporal network, while nouns were associated with a left inferior-medial temporal cluster, and overlapping activation was found for the two grammatical categories in the left lateral fusiform gyrus (Faroqi-Shah et al., 2018). Other studies utilizing meta-analytical approaches and extensive reviews of literature, however, challenged those findings by highlighting inconsistencies across studies and various confounds, such as differences in semantic properties and cognitive demands (Crepaldi et al., 2011, 2013; Vigliocco et al., 2011). Thus, this latter group of studies argue either that grammatical category is not a lexical organizational principle in the brain (Vigliocco et al., 2011) or that verbs and nouns are represented in a left fronto-temporo-parietal network in close proximity to each other (Crepaldi et al., 2011, 2013).

Evidence from Neurostimulation

Given that functional imaging is a correlational technique, it is difficult to establish a causal relationship between the active region and the relevant function (Vukovic et al., 2017). Transcranial magnetic stimulation (TMS), on the other hand, can help determine whether a brain area is necessary for a given function by revealing any causal relationships between the brain area and its supposed function (Pascual-Leone et al., 2000). TMS can be applied in different ways; for instance, as a single pulse during a certain motor or cognitive task, or as a series of repeated pulses with a certain frequency and duration (Oberman, 2014). This latter approach is referred to as repetitive TMS (rTMS), which we adopted in the present study. Repetitive TMS can modulate activity of a brain region through inhibitory low-frequency stimulation (e.g., 1 Hz) or excitatory high-frequency stimulation (usually > 5 Hz). When applied at low frequencies and for a short period (e.g., 10 minutes), rTMS can induce transient changes in cortical excitability and behavior, a procedure referred to as virtual lesion (Pascual-Leone et al., 2000; Vukovic et al., 2017). The effects of virtual

lesions are short-lived, lasting about 5-20 minutes depending on the stimulation parameters (Chen et al., 1997; Jin Hilgetag, 2008; Mottaghy et al., 2002). This approach allows testing for any change in behavior/performance from pre- to post-stimulation, thereby showing whether the relevant region is necessary for the relevant function. rTMS is a non-invasive tool that has been shown not to have important adverse effects provided that the established safety guidelines are followed (Rossi et al., 2009, 2021; Vukovic et al., 2017). Several rTMS studies investigated the cortical organization of nouns and verbs (Cappelletti et al., 2008; Repetto et al., 2013; Shapiro et al., 2001; Sparing et al., 2001). Using this technique, it was shown, for instance, that suppression of part of the left prefrontal cortex with low-frequency rTMS resulted in a slowdown (i.e., higher latencies) in verb production performance, while production of nouns did not change post- relative to pre-stimulation (Cappelletti et al., 2008; Shapiro et al., 2001). These rTMS studies associated left prefrontal regions with processing verbs compared to nouns, while posterior regions including Wernicke's area have been less studied using rTMS (for a review, see Vigliocco et al., 2011).

Current Study

As reviewed above, there is mixed evidence for the cortical separation of nouns and verbs from neuropsychology, neuroimaging, and neurostimulation. Against this background, the current rTMS study examines the dissociation of action and object naming in the left prefrontal cortex spanning Broca's area (Experiment 1) and the left posterior temporal cortex spanning Wernicke's area (Experiment 2), seeking evidence from a less-studied language, namely, Turkish. In both experiments, low-frequency (1 Hz), inhibitory stimulation was administered at 100% of motor threshold for 10 minutes (total number of pulses = 600). Previous research has shown that stimulation at this frequency and for this duration, and hence with this number of pulses, leads to suppression of the stimulated brain areas, causing behavioral slowdowns in language-related tasks (Choi et al., 2015; Knecht et al., 2002). Based on previous research, we developed two related hypotheses for the present study:

H1: Suppression of Broca's area in Experiment 1 will lead to a significant interaction between session (pre- versus post-stimulation) and stimulus category (actions versus objects), whereas suppression of Wernicke's area in Experiment 2 will not lead to such a significant interaction.

Thus, H1 suggests that the distinction between actions and objects will be observed for Broca's area, in line with previous neuropsychological and neuroimaging findings which showed this distinction more for frontal regions than temporal regions as reviewed above (Breedin et al., 1998; Caramazza & Hillis, 1991; Damasio & Tranel, 1993; Goodglass et al., 1966; McCarthy & Warrington, 1985; Vigliocco et al., 2011).

H2: Suppression of Broca's area will lead to a significant slowdown in naming actions but not objects.

Hence, H2 aligns with previous research which associated Broca's area with actions more than objects (Cappelletti et al., 2008; Shapiro et al., 2001).

Methods

Participants

Thirty-six participants (13 males, 23 females) took part in the study. The participants' ages ranged from 20 to 44 ($M = 23.1$; $SD = 4.9$). All participants were recruited from the university campus where the study was conducted. All participants were either university students or graduates. The inclusion criteria for the study were being an adult native Turkish speaker, being right-handed, having no known neurological or psychiatric conditions, and meeting the safety criteria for TMS experiments. For the safety criteria, a Turkish translation of a screening questionnaire (Rossi et al., 2011) was used in keeping with the latest TMS safety guidelines (Rossi et al., 2009, 2021). Thus, people who had a history of epilepsy or experienced one seizure in their life, had cochlear implants, had any metal or implant in their head, or were on epileptogenic medications, i.e., medications lowering the seizure threshold, were excluded from the study.

The sample size was determined using G*Power (Faul et al., 2007, 2009). This was done separately for two planned analyses in line with our hypotheses. Analysis 1 interrogated any interaction between session (pre versus post) and stimulus category (actions versus objects). For Analysis 1, the following configurations were used in G*Power to calculate power and sample size: F tests, ANOVA: Repeated measures, within factors. Analysis 2, on the other hand, examined any pre- to post-stimulation difference for actions and objects, separately, which aims to break down the interaction in Analysis 1 if it turns out to be significant. For Analysis 2, the following configurations were used in G*Power: t tests, Means: Difference between two dependent means (matched pairs), one tailed. Based on medium effect sizes, an alpha level of 0.05 and 0.90 power, the required sample size was determined as 30 for Analysis 1, and 36 for Analysis 2. Therefore, we took the more conservative sample size ($n = 36$).

Of the 36 participants, all participated in Experiment 1. However, the recording device malfunctioned while recording one participant's naming data in Experiment 1, resulting in data loss; hence, that participant was excluded from the analyses of Experiment 1. Therefore, 35 participants contributed data to Experiment 1. All 36 participants were also invited to participate in Experiment 2. Of these, eight failed to show up for personal reasons; therefore, 28 participants took part in Experiment 2. Note that with 28 participants in Experiment 2 we still retained $> .80$ power for both analyses. Also note that although the power analysis was based on ANOVA and t tests, linear mixed-effects models were actually used in data analyses (see the Data Analyses section below) because they have been shown to have certain advantages over ANOVA-style tests, such as providing greater power (Brown, 2021).

Materials

Four sets of black-and-white drawings of objects and actions were prepared using The International Picture Naming Project (IPNP) database (<https://crl.ucsd.edu/experiments/ipnp/>) (Székely et al., 2003, 2005). The presentation order of the picture sets was counterbalanced such that each list was used equally often in the first, second, third, and fourth sessions (pre- and post-stimulation sessions of

Experiment 1 and Experiment 2). Each set consisted of novel pictures depicting objects ($n = 15$) and actions ($n = 15$) with 3 practice stimuli for objects and actions each.

Given that naming a picture entails various levels of processing, including visual and conceptual processing, and lexical selection and retrieval from the mental lexicon (Levelt et al., 1999), multiple factors can influence the naming process in addition to category difference (actions versus objects), which is the main focus of the present study. To minimize potential confounds that can affect picture naming, the following values were extracted from the IPNP database for each picture that we used: The number of alternative names for each picture, name agreement (i.e., H index; Snodgrass & Vanderwart, 1980), naming latencies, and objective age of acquisition. These values were obtained from naming experiments and corpus analyses in English. The number of alternative names and name agreement reflect the consistency of responses to a given picture across participants (Snodgrass & Vanderwart, 1980; Székely et al., 2005). For instance, if most participants name a picture with the same word (e.g., *whisper*), then that picture will have a small number of alternative names (just *whisper*) and high name agreement across participants. However, if different participants come up with different names for a picture (e.g., *laugh*, *smile*, *giggle*), then that picture will have a higher number of alternative names and lower name agreement. As for naming latencies, these are response times starting from presentation of the picture on the computer screen until the participant produces a name for it. Two separate measures of naming latencies were used: Latencies for all valid trials; i.e., where participants produced a name for the picture, and for dominant responses only; i.e., the name that was used by the largest number of participants. Objective age of acquisition refers to the age at which a word is acquired throughout lifespan and this measure used in the present study is based on published norms for the American version of the MacArthur Communicative Development Inventories (Fenson et al., 1994), as available on the IPNP database (Székely et al., 2003, 2005).

In addition, conceptual complexity, i.e., number of objects, animals or persons depicted in each picture, and visual complexity (based on digitized picture size) measures were acquired from the same database. Furthermore, using a balanced corpus of the Turkish language (Turkish National Corpus, Aksan et al., 2012), surface and lemma frequencies were obtained for each word corresponding to each picture, as judged by the researchers, and entered in the analyses as both raw and logged frequencies. Surface frequency, also known as word-form frequency, refers to the number of instances of a word form (e.g., *play* as it is written) within a corpus, while lemma frequency counts all inflected forms of a word (e.g., *play*, *plays*, *played*, *playing*; Brysbaert & New, 2009). In sum, we considered various visual, conceptual, and other psycholinguistic confounds to ensure rigorous comparison of objects and actions, while also matching the lists of stimuli presented in different sessions.

A series of one-way ANOVAs showed that the four picture sets did not significantly differ in terms of any of the above-mentioned variables, either when all stimuli (actions and objects) were grouped together or when actions and objects were analyzed separately [$F_s < 1.939$, $p_s > .133$]. When all the action and object stimuli were directly compared, they did not significantly differ in terms of number of alternative names, name agreement (H index), objective age of acquisition, conceptual complexity, and visual complexity [$t_s <$

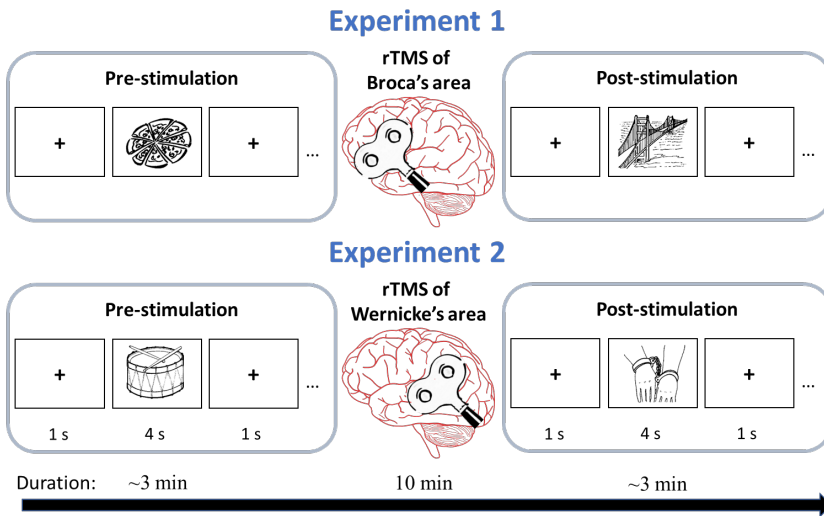
.506, $ps > .614$], but they did differ significantly on naming latencies (higher latencies for actions than objects), and lemma and surface frequency measures (higher lemma but lower surface frequencies for actions than objects) [$ts > 2.001$, $ps < .049$]. Although frequency was not matched between objects and actions overall, this confound, in addition to several others, was added to the statistical models as a covariate (see the Data Analyses section below).

Note that these analyses were conducted prior to the experiments; therefore, the English naming data from the IPNP database were used to counterbalance the stimuli as much as possible before the actual Turkish data were collected. After the experiments were conducted, however, the Turkish naming data were used in further analyses. In addition, after data collection, the lemma frequencies for each named word were again obtained using the Turkish National Corpus, and these frequencies were used in further analyses. However, the English-based objective age of acquisition values were used in further analyses. Finally, the name agreement values were obtained from a recently created naming database for Turkish whenever available (Eskioğlu, 2022).

Procedure

Ethical approval was obtained from the Institutional Review Board of Istanbul Medipol University (Date: 18/03/2021; Number: 346). As illustrated in Figure 1, two experiments, each including a pre-stimulation session and a post-stimulation session, were conducted on two separate days. The same picture naming procedure was used in both experiments, with the only difference being the stimulation site. Experiment 1 always preceded Experiment 2, and at least one day (and at most one week) intervened between the two experiments to ensure washout of residual effects from the preceding stimulation before the second experiment was performed. In the experiments, the participants were asked to name the presented action or object as soon as it was presented on the screen by using a single word and avoiding expressions indicating thinking or hesitation. Actions and objects were presented in separate blocks, the presentation order of which was counterbalanced (actions and objects were presented equally often as the first and second blocks within each session). Audio recordings were obtained during the experiments to be used to calculate naming performance (accuracy and latency). Following instructions, a fixation cross was presented at the center of the screen for one second, which was accompanied by a click sound to mark timing of stimulus presentation in the audio recording. After the fixation, a picture was presented on the screen for four seconds, at the end of which the picture disappeared and another trial was initiated starting with a fixation cross. Each naming session took approximately three minutes to complete. Before each naming session, a separate task which is not addressed here and which lasted approximately three minutes was administered to the participants, and immediately after this task the participants performed the naming tasks. Thus, the post-stimulation naming session was completed within approximately six minutes from the end of rTMS, which is largely within the time window of poststimulation rTMS effect (between 5-20 minutes), as shown in previous research (Chen et al., 1997; Jin & Hilgetag, 2008; Mottaghy et al., 2002).

Figure 1. Experimental Procedure



rTMS Parameters

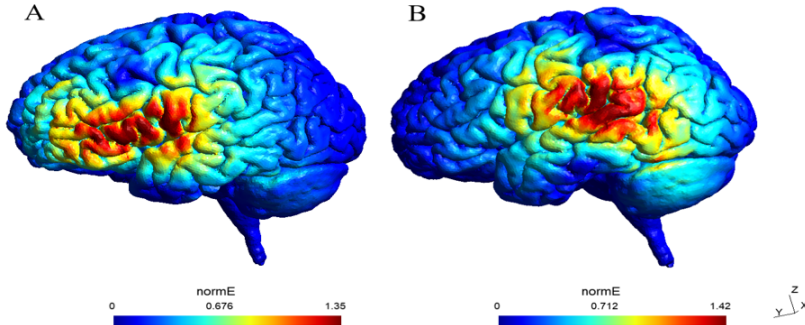
rTMS was delivered with a Neuro-MS/D Advanced Therapeutic Transcranial Magnetic Stimulator (Neurosoft, Ivanovo, Russia) using a figure-of-eight coil. In both experiments, low-frequency (1 Hz), inhibitory stimulation was administered at 100% of motor threshold for 10 minutes without an inter-train interval (total number of pulses = 600). The participants' motor threshold was determined as the lowest percentage of stimulator output capable of causing a visible twitch in the thumb muscle five out of 10 times (Pridmore et al., 1998). The same motor threshold determined for the participants in Experiment 1 was also used in Experiment 2. The stimulation parameters adopted in the present study are within the safe limits according to the current TMS safety guidelines (Rossi et al., 2009, 2021). As advised in these guidelines, we report any adverse/side effects during or after the experiments. No adverse events were observed during the study. The participants were requested to report any side effects of the stimulation following the two experiments. Of all participants, only two reported headaches following Experiment 1, which resolved within the same day. No side effects were reported after Experiment 2.

The two experiments differed only in the stimulation site, as illustrated in Figure 1. In Experiment 1, the coil was placed over Broca's area (left inferior frontal gyrus), while in Experiment 2 the coil was placed over Wernicke's area (left posterior superior temporal gyrus). The stimulation sites were identified using the international 10-20 system with an EEG electrode cap. Specifically, the midpoint of F7-FC5 corresponded to the left IFG, whereas electrode CP5 corresponded to the left posterior STG (Duncan et al., 2020).

SimNIBS Version 3.2.5 (Thielscher et al., 2015) was used to simulate electrical field distribution based on the stimulation sites implemented in this study and the default settings in the program. As illustrated in Figure 2, the stimulation sites in Experiment 1 and Experiment 2 were associated with the greatest electric field strength in Broca's and Wernicke's areas, respectively. Please note that a figure-of-8 coil

(Magstim_70mm_Fig8.nii.gz) that was closest in shape and dimensions to the coil used in this study was entered in the simulation.

Figure 2. Simulated Electric Field for Stimulation of Broca's Area in Experiment 1 (A) and Wernicke's Area in Experiment 2 (B)



Note. Color bars indicate norm or strength of the electric field. The simulation was performed on SimNIBS. Please note that low-frequency inhibitory rTMS was applied and that the heat map reflects strength of a single pulse.

Data Analyses

The audio recordings taken during the experiments were analyzed using Praat (Boersma & Weenink, 2018) to determine the click onsets that provided a timestamp for the upcoming picture presentation and the naming onsets, which were used to calculate naming latencies (time from picture presentation until naming onset). The named words were also coded. Trials with named words that were judged to correspond to the depicted objects or actions were coded as accurate. Trials were coded as inaccurate if no response was made, if object pictures were named as actions or vice versa, if words not closely related to the depicted items were produced, or if more than one word was produced for a given picture. Only the naming latencies for accurate trials were entered in the analyses. To account for a possible practice effect on overall reaction times, the naming latencies were adjusted using the following formula: naming latency * grand mean / session mean (Holland & Lambon Ralph, 2010). This adjustment and scaling helped eliminate any generic speeding effects and equalize the latencies in pre- and poststimulation sessions (Holland & Lambon Ralph, 2010).

The statistical analyses of the naming latency data were conducted in R version 4.1.2 (R Core Team, 2013) using the lme4 package version 1.1.27.1 (Bates et al., 2015) and employing linear mixed-effects models (LMMs). LMMs with the same parameters were used to analyze the naming data of Experiment 1 and Experiment 2, separately. LMMs included subjects and items as random effects, and the following variables as fixed effects: session (pre-stimulation, post-stimulation), category (action, object), and the interaction between session and category. The following psycholinguistic variables were also added to the models as covariates to provide control for relevant confounds and to account for additional variance in the data: natural log of lemma frequency, visual complexity, conceptual complexity, age of acquisition, H index, presentation order of the pictures (i.e., trial order) within a session, and named word length. The maximal random-effects

structure permitted by the design was initially used (Barr et al., 2013; cf. Matuschek et al., 2017); however, when this led to convergence and/or singular fit errors, the random-effects structure was simplified by removing correlations between random effects and, if that did not resolve the problem, by removing random slopes and their correlations (Brown, 2021). Random-effects variances were inspected to ensure that model estimation went smoothly.

Session was deviation coded as -0.5 and 0.5 for pre-stimulation and post-stimulation, respectively. Likewise, category was deviation coded as -0.5 and 0.5 for objects and actions, respectively. With deviation coding, observed effects reflect deviations from a grand mean and, thus, correspond to main effects/interactions as in the conventional ANOVA style (Barr et al., 2013). All continuous predictors were scaled and centered. Naming latencies were analyzed only for correctly answered trials. The latencies were natural log-transformed to approximate normal distribution (Box & Cox, 1964). The lmerTest package version 3.1.3 (Kuznetsova et al., 2017) in R was used to calculate the p values. Significant interactions were followed up with planned comparisons based on the estimated marginal means from the relevant models, using the emmeans package (Lenth, 2021). All data and analyses codes are available at <https://doi.org/10.17605/OSF.IO/J5HGS>.

Results

Experiment 1

Accuracy was very high in both the pre-stimulation session ($M = 97\%$, $SD = 6\%$) and post-stimulation session ($M = 98\%$, $SD = 4\%$). Due to lack of variance in accuracy scores, they were not entered in statistical analyses.

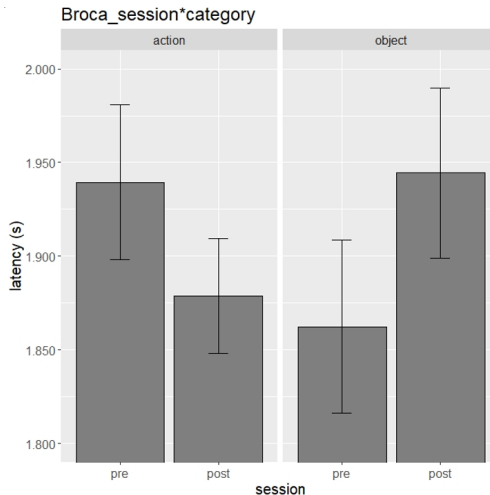
As summarized in Table 1, LMM on naming latencies for accurate trials revealed several significant effects. It was found that as conceptual complexity increased, naming latencies also increased, indicating the difficulty of naming conceptually complex pictures ($\beta = .030$, $SE = .009$, $t = 3.186$, $p = .002$). Another significant effect was age of acquisition, which showed that words acquired later in life were associated with greater naming latency than words acquired earlier ($\beta = .036$, $SE = .009$, $t = 4.042$, $p < .001$). A further significant effect was the H index, which measures name agreement. The results showed that as the H index increased; i.e., name agreement decreased, the latencies also increased, reflecting the difficulty with pictures that pose greater ambiguity ($\beta = .061$, $SE = .009$, $t = 6.714$, $p < .001$).

Table 1. Summary of the LMM Fixed Effects for Log-Transformed Naming Latencies for Accurately Named Words in Experiment 1 (Broca) and Experiment 2 (Wernicke)

Predictor	Experiment 1 (Broca)				Experiment 2 (Wernicke)			
	Coef	SE	t	p	Coef	SE	t	p
Session	.005	.008	.629	.530	.004	.008	.534	.593
Category	-.007	.020	-.363	.717	-.007	.023	-.325	.745
Lemma frequency	.009	.008	1.060	.290	.016	.009	1.671	.095
Visual complexity	-.017	.010	-1.779	.078	-.013	.010	-1.232	.220
Conceptual complexity	.030	.009	3.186	.002	.031	.010	2.968	.004
Age of acquisition	.036	.009	4.042	< .001	.036	.010	3.688	< .001
H index	.061	.009	6.714	< .001	.060	.010	6.049	< .001
Presentation order	.005	.004	1.056	.291	.014	.004	3.206	.001
Length	.015	.009	1.636	.103	-.002	.009	-.174	.862
Session:category	-.052	.015	-3.354	< .001	-.017	.016	-1.074	.283

Finally, a significant interaction was observed between session and category ($\beta = -.052$, $SE = .015$, $t = -3.354$, $p < .001$). As illustrated in Figure 3, actions showed a reduction in naming latency from pre-stimulation ($M = 1.940$, $SD = .244$) to post-stimulation ($M = 1.879$, $SD = .181$) of Broca’s area. However, objects exhibited an increase in naming latency from pre-stimulation ($M = 1.862$, $SD = .273$) to post-stimulation ($M = 1.944$, $SD = .269$). To interrogate this interaction, the estimated marginal means of naming latencies associated with the pre- and post-stimulation sessions derived from LMM were compared at each level of category (actions, objects). It was found that for objects, the post-stimulation naming latencies were significantly greater than the pre-stimulation latencies ($\beta = -.031$, $SE = .011$, $t = -2.813$, $p_{corr} = .005$). For actions, on the other hand, the pre- to post-stimulation difference failed to reach statistical significance ($\beta = .021$, $SE = .011$, $t = 1.917$, $p_{corr} = .055$).

Figure 3. Interaction Effect of Session*Category on Adjusted Naming Latencies in Experiment 1



Note. Error bars show standard error.

Experiment 2

As before, accuracy was very high in both the pre-stimulation session ($M = 99\%$, $SD = 2\%$) and the post-stimulation session ($M = 99\%$, $SD = 3\%$) of Experiment 2. As summarized in Table 1, the main significant effects identified in Experiment 2 were conceptual complexity, age of acquisition, and H index, which were found to influence the naming latencies in the same way as in Experiment 1. This result supports the stability and robustness of these effects on picture naming latencies. Also, presentation order, which is a covariate of no interest, was significant in Experiment 2. Importantly, unlike Experiment 1, Experiment 2 failed to produce a significant interaction between session and category ($\beta = -.017$, $SE = .016$, $t = -1.074$, $p = .283$).

Robustness Analysis: Reanalysis of Experiment 1

To test whether the lack of significant session*category interaction in Experiment 2 was due to its lower power ($n = 28$) compared to Experiment 1 ($n = 35$), another LMM with the same parameters was fitted to the data collected in Experiment 1 only from the same participants that also participated in Experiment 2 ($n = 27$). This model with lower power also yielded a significant interaction of session*category ($\beta = -.040$, $SE = .017$, $t = -2.300$, $p = .022$), along with the other significant effects for Experiment 1, as reported in Table 1. Furthermore, when the estimated marginal means of naming latencies associated with pre- and post-stimulation sessions were compared at each level of category (actions, objects) with this down-sampled data, the same results were obtained as those in the original analyses. In other words, it was found that for objects, the post-stimulation naming latencies were significantly greater than the pre-stimulation latencies ($\beta = -.027$, $SE = .012$, $t = -2.222$, $p_{corr} = .026$). For actions, on the other hand, the pre- to post-stimulation difference failed to reach statistical significance ($\beta = .013$, $SE = .012$, $t = 1.029$, $p_{corr} = .304$). This result indicates that the difference between Experiment 1 and Experiment 2 in regard to the interaction of session*category cannot be explained by a difference in statistical power, and that the significant session*category interaction and the follow-up analysis in Experiment 1 were robust.

Discussion

Using inhibitory, low-frequency rTMS with a virtual lesion approach, the present study tested the dissociation of actions and objects in two language-related regions: Broca's and Wernicke's areas. Linear mixed models were fitted to the naming latency data with session (pre- and post-stimulation), category (action, object), and session*category interaction as predictors, in addition to several psycholinguistic covariates, separately for Broca's stimulation (Experiment 1) and for Wernicke's stimulation (Experiment 2). The findings revealed that conceptual complexity of the pictures to be named, age of acquisition of the target word, and name agreement (H index) had a consistent and robust effect on naming latencies. Importantly, only the stimulation of Broca's area in Experiment 1 produced a significant interaction between session and category. This interaction was largely driven by a significant increase in naming latencies from pre- to post-stimulation for objects following stimulation of Broca's area. This finding suggests that Broca's area, but not Wernicke's area, shows a dissociation between actions and objects in Turkish.

Of the psycholinguistic covariates included in the statistical models, only conceptual complexity of the pictures to be named, age of acquisition of the target word, and name agreement (H index) had a consistent and robust effect on naming latencies. These variables have been shown to modulate naming latencies in previous studies conducted in English (Székely et al., 2003, 2005) and Turkish (Eskioğlu, 2022). However, we did not find a significant effect of word category, unlike previous studies (Mätzig et al., 2009; Székely et al., 2005). This lack of a significant word category effect could be due to the fact that nouns and verbs were matched on a number of psycholinguistic confounds, including surface and lemma frequency, visual complexity, conceptual complexity, age of acquisition, number of alternative names for each picture, name agreement (i.e., H index), and word length, through matching the stimuli on these variables prior to data collection and/or including them in statistical models as covariates afterwards. Indeed, some of these variables have been suggested to confound the grammatical distinction between nouns and verbs (Vigliocco et al., 2011). In a similar vein, a previous study on verb-noun naming in Parkinson's disease and control participants found higher accuracy and faster naming latencies for nouns than verbs in Turkish (Bayram et al., 2021). However, this difference disappeared when certain semantic and conceptual covariates, some of which overlap with the covariates used in the present study, were added to the statistical model, suggesting that these variables explained the noun-verb difference.

The main finding of the present study is that only the stimulation of Broca's area led to a significant interaction between session (pre- and post-stimulation) and word category. This finding confirms our first hypothesis and suggests that Broca's area, but not Wernicke's area, exhibits a dissociation between actions and objects in Turkish. This finding is consistent with the bulk of neuropsychological studies involving individuals with aphasia and rTMS studies in healthy individuals, which provided clearer support for verb-noun distinction in the frontal lobe, including Broca's area, than in the temporal lobe, including Wernicke's area (Mätzig et al., 2009; Vigliocco et al., 2011). Of note, this finding was obtained even after controlling for the confounding variables described in the preceding paragraph. However, it should be acknowledged that certain semantic confounds (action- or motor-relatedness, imageability), which have been shown to correlate with and influence the grammatical distinction between nouns and verbs (Vigliocco et al., 2011), could not be controlled in the present study. In particular, as grammatical class (noun/verb) is highly correlated with meaning, nouns generally refer to objects, whereas verbs generally refer to actions (Vigliocco et al., 2011). Thus, the present findings cannot be unequivocally attributed to a noun-verb distinction in Broca's area and should be interpreted as support for action versus object difference, which is a liberal proxy for grammatical class that should be addressed in its own right in future studies, ideally utilizing various tasks and carefully matched stimuli.

The significant interaction between session and word category was mainly driven by a significant increase in naming latencies from pre- to post-stimulation for objects following stimulation of Broca's area, while the opposite pattern was observed for actions with marginal significance. This finding does not support our second hypothesis, which states that suppression of Broca's area will lead to a significant slowdown in naming actions but not objects. Indeed, to the contrary, the present finding seems to suggest that performance in object naming deteriorates following inhibition of Broca's area, thus

linking this region with objects/nouns rather than actions/verbs, which contradicts the vast majority of neuropsychology, brain imaging and stimulation literature (as reviewed in Crepaldi et al., 2013, 2011; Faroqi-Shah et al., 2018; Vigliocco et al., 2011). Although this is not the first study to show an association between Broca's area and nouns/objects relative to verbs/actions (Berlingeri et al., 2008; Siri et al., 2008; Strijkers et al., 2019), such observations were generally attributed to other factors, including general processing demands, rather than a grammatical class distinction. Whether the present findings are real effects or an artifact of the task or stimuli remains to be determined in future replication efforts. However, it seems unlikely that potential confounds in the stimuli/picture sets are the culprit, given the randomization procedure and the various relevant psycholinguistic covariates used to match the stimuli and entered in statistical models. If the effect is real and Broca's area is associated more with objects/nouns than with actions/verbs, this could perhaps relate to typological and grammatical differences between Turkish and previously studied languages such as English. For instance, the noun advantage in the verb-noun asymmetry in language acquisition was shown to be less pronounced for Turkish compared to Indo-European languages such as German, French, and Dutch (Kauschke et al., 2007; Özcan et al., 2016; cf. Altınkamuş et al., 2014). This possibly attenuated asymmetry between verbs and nouns in Turkish may have contributed to the current findings.

Although the interaction between session and word category was mainly driven by pre- to post-stimulation difference for object naming, there was also a marginally significant pre- to post-stimulation decrease in latencies or speedup for action naming. rTMS at low frequencies (e.g., 1 Hz) has typically been shown to have an inhibitory effect on the stimulated area (Cappelletti et al., 2008; Chen et al., 1997; Di Lazzaro et al., 2011; Mottaghy et al., 2002; Repetto et al., 2013). However, the mechanisms of action of rTMS are not fully understood. Furthermore, it was also shown that 1 Hz rTMS may not always be inhibitory and may even produce excitatory effects (Caparelli et al., 2012). Along these lines, it could be argued that the present finding of decreased naming latency for actions following stimulation of Broca's area, albeit marginally significant, may still suggest involvement, at a certain level, of this region with action naming, while this involvement seems to be in a different direction from object naming. However, this marginally significant speedup for action naming was far above the statistical threshold in the robustness analysis of Experiment 1 using the data from the same participants who also participated in Experiment 2. Future rTMS studies comparing low and high frequency (e.g. 1 Hz vs. 10 Hz) stimulation of Broca's area can shed more light on this issue.

The present study has several limitations that need addressing. First, although various psycholinguistic covariates (frequency, visual complexity, conceptual complexity, age of acquisition, number of alternative names, name agreement, and word length) were used to match the stimuli and lists and/or were entered in statistical models, we could not control certain semantic confounds (action- or motor-relatedness, imageability) relevant to the distinction between nouns and verbs (Vigliocco et al., 2011) and, hence, may have affected the present results. Second, Experiment 1 (stimulation of Broca's area) always preceded Experiment 2 (stimulation of Wernicke's area), which may have led to unintended differences (e.g., practice effects) between the experiments. However, given that completely different, although matched, stimuli were used in Experiments 1 and 2, and that there was

an interval of at least one day and up to one week between the two experiments, we doubt that this potential order/practice effect substantially impacted the results. Even if this led to a practice effect, this would be expected on the overall results, not for actions or objects specifically. Finally, although we assumed that 1 Hz rTMS stimulation would lead to suppression of the target brain region in line with a large body of research, the mechanisms of action of rTMS may be more complex than this. Therefore, the present findings should be interpreted cautiously given these potential limitations.

In conclusion we used inhibitory, low-frequency rTMS to investigate the dissociation of action and object naming in Broca's and Wernicke's areas in Turkish. Using linear mixed models that controlled various psycholinguistic covariates, we found robust association of Broca's area, but not Wernicke's area, in the distinction between naming objects and actions. Suppression of Broca's area led to a significant and robust increase in naming latencies, or slowdown, for objects, and to a marginally significant, but not robust, reduction in naming latencies, or speedup, for actions. Although these findings suggest stronger association of Broca's area in object naming relative to action naming for Turkish, we caution that this conclusion may be premature and should be addressed in future studies utilizing different stimulation parameters (low vs. high frequency stimulation) and different tasks (e.g., lexical decision), and considering several other confounding factors, including motor relatedness and imageability.

Data Availability Statement

All anonymized data and analyses codes associated with the present study are available at the following link: <https://doi.org/10.17605/OSF.IO/J5HGS>

Ethics Committee Approval: Approval was received from Istanbul Medipol University Non-Interventional Clinical Research Ethics Committee. Decision number: 346. Date: 18/03/2021

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