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The effects of intermittent theta burst stimulation on video action naming in healthy young adults

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1. Introduction

Picture naming is a task commonly used in several clinical assessments, such as speech-language pathology and neuropsychology (Mason and Nickels, 2022). During a picture naming task, individuals are presented with images and asked to accurately name the objects or actions depicted. The task of picture naming involves a series of complex cognitive processes (Caramazza et al., 1990; Dell, 1986; Friederici, 2017; Levelt, 1989). The first step is the visual recognition of the image. This activates the structural description system that analyzes and recognizes the target image. The second step is the semantic activation of the concept depicted by the image recognized in the previous step. The third step is lexical selection, where the person selects the phonological form of the word that corresponds to the concept being expressed. The following step involves the phonetic encoding and articulation necessary for the oral output. Phonetic encoding involves computing the gestural instructions for articulation. Finally, the process ends with the actual articulation (i.e., the oral production of the name evoked by the image). This is the stage where the word is physically produced (e.g., Caramazza et al., 1990; Dell, 1986; Friederici, 2017; Levelt, 1989).

Neurolinguistic models establish connections between the various stages of picture naming and specific brain regions (Duffau, 2014; Hickok and Poeppel, 2004; Indefrey and Levelt, 2004). Although there is not a consensus regarding the link between neural structure and function, these models commonly distinguish two distinct pathways (Drane and Pedersen, 2019; Friederici, 2011; Jarret et al., 2022). First, the bilateral ventral pathway, located within the ventral part of the cerebrum, is essential for semantic language processing (Duffau, 2014). This ventral processing stream plays a crucial role in mapping visual stimuli to meaning and is vital for conceptually driven word retrieval (Dick and Tremblay, 2012; Faulkner and Wilshire, 2020; Hickok and Poeppel, 2004; Saur et al., 2008). In the context of picture naming, the middle occipital gyrus (MOG) and inferior temporal gyrus (ITG) connect to the inferior frontal gyrus (IFG) pars orbitalis via the inferior fronto-occipital fasciculus (IFOF), forming a direct lexicosemantic pathway (Akinina et al., 2019; Jarret et al., 2022; Shimotake et al., 2015). Second, the left-lateralized dorsal pathway, located in the more dorsal regions of the cortex and associated white matter tracts, is involved in phonological language processing (Hickok and Poeppel, 2007). The dorsal stream is essential for sound-level speech planning, including the retrieval of phonological information about words and the construction of a motor plan for the articulation of the desired phoneme sequence. Additionally, the dorsal stream is involved in the top-down control of lexical retrieval and word selection (Faulkner and Wilshire, 2020; Hickok and Poeppel, 2007). The dorsal pathway for picture naming includes the interconnection of the ITG, superior temporal gyrus (STG), IFG pars orbitalis, precentral gyrus (PCG), and supplementary motor area (SMA) via the arcuate fasciculus (AF) and frontal aslant tract (FAT) (Jarret et al., 2022; Piai and Eikelboom, 2023). These two pathways operate in parallel.

Most studies on oral naming have focused on the production of object names (refer to the systematic review by Piai and Eikelboom, 2023). However, research has examined the neural differences between naming nouns and actions. Actions are a subcategory of verbs that describe a process executed by someone or something (Rispoli, 1991). A comprehensive review by Vigliocco et al. (2011) showed that nouns and verbs share many of the same brain regions for language production and comprehension. For example, both neuroimaging and non-invasive brain stimulation studies have demonstrated the contribution of the left IFG to the oral production of both nouns and verbs (Arheix-Parras et al., 2021; Klaus and Hartwigsen, 2019; Krieger-Redwood and Jefferies, 2014; Yao et al., 2020). However, the overlap of the neural patterns for the processing of nouns and verbs is not complete. This indicates different specialized pathways for the processing of nouns and verbs. The action verb network, for instance, shows strong functional connectivity, particularly between the middle temporal gyrus (MTG) and STG with the left IFG, insula, and left MOG (Crepaldi et al., 2013;

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Vigliocco et al., 2011; Yang et al., 2017). Naming actions frequently activates a fronto-temporo-parietal network that includes the IFG, the ventral premotor cortex, the somatosensory cortex, the anterior supramarginal gyrus, and the posterior MTG (Courson and Tremblay, 2020; Yang et al., 2017). This network is primarily left-lateralized. Additionally, the middle frontal gyrus (MFG) plays a significant role in the oral production of action verbs and is involved in word retrieval from semantic memory (Cappa et al., 2002; Cappelletti et al., 2008; Cotelli et al., 2010, 2012). These findings underscore the complexity of the neural mechanisms involved in action naming.

Our current understanding of action naming processes comes mostly from studies using static formats such as pictures or drawings. However, research indicates that both healthy individuals and persons with language disorders name action better when videos depicting the actions are used as compared to pictures of actions (de Almeida et al., 2021; Spigarelli and Wilson, 2022). Given that action verbs are inherently dynamic, videos offer a more accurate representation of these actions, potentially engaging different neural networks compared to static images (den Ouden et al., 2009).

To the best of our knowledge, no studies have specifically investigated the neural network involved in action naming using video stimuli. The objective of the present study is to determine whether the neural network for naming actions from videos is comparable to the network for naming actions from pictures. While the involvement of the IFG and the MFG in action naming with static images is well-documented in the literature (Bolgina et al., 2022; Cappa et al., 2002; Cotelli et al., 2010; Ward et al., 2022), it remains unclear whether these regions are also recruited for action naming when using video stimuli. Therefore, we will target the left IFG and left MFG to see if they are also involved in naming actions depicted in videos. We will use intermittent theta-burst stimulation (iTBS). iTBS is a specific form of repetitive transcranial magnetic stimulation (rTMS). rTMS is among the non-invasive brain stimulation (NIBS) techniques that have gained popularity for studying causal relationships between language functions and their underlying neural processes. rTMS allows the depolarization of cortical neurons through electromagnetic induction. Typically, an 8-shaped stimulation coil is placed on the scalp and used to deliver a magnetic field, which, in turn, induces electric currents in brain regions beneath the coil. Depending on the protocol used, rTMS can either facilitate or inhibit the functioning of targeted neuronal networks (Huang et al., 2005). iTBS involves delivering bursts of magnetic stimulation in a pattern designed to increase cortical excitability. iTBS uses short bursts of high-frequency stimulation (theta burst) intermittently and has the advantage of a shorter duration of stimulation (around 3 min) compared to traditional rTMS protocols. iTBS can induce short- and long-term plasticity in the brain, leading to improved performance across various domains, including cognitive (e.g., Kim et al., 2019; Martin et al., 2023) and speech/language processing (e.g., Brisson and Tremblay, 2021; Griffis et al., 2016; Szaflarski et al., 2018). To date, no study has investigated action naming using video stimuli in conjunction with iTBS. This approach will provide more comprehensive insights into the brain network for video action naming.

2. Method

2.1. Participants

Thirty-six healthy participants were divided into two groups of 18 participants each: iTBS and placebo iTBS. In the iTBS group, participants (50 % female) were between 22 and 33 years of age ($M = 27.22$ years, $SD = 3.13$). Their educational level ranged between 13 and 19 years ($M = 17.67$, $SD = 1.88$). In the placebo iTBS group, participants (55 % female) were between 20 and 33 years of age ($M = 25.89$ years, $SD = 4.63$) and their educational level ranged from 14 to 19 years ($M = 17.06$, $SD = 1.47$). Inclusion criteria were that all participants had French as their native language. In each group there were 14 participants with Quebec French as their native language and 4 participants with French from France as their native language. All participants had normal general cognition operationalized as a Montreal Cognitive Assessment score of at least 26 out of 30 (MoCA; Nasreddine et al., 2005), and were right-handed, with a score of at least 7 points in the Edinburgh Handedness Inventory (Oldfield, 1971).

Exclusion criteria included the absence of history of neurological disorders, learning disabilities, stroke, psychiatric disorders, alcoholism, or uncorrected visual or auditory impairments measured via a screening questionnaire (self-reported). All participants were compatible for MRI and rTMS as measured by the screening questionnaire by Rossi et al. (2011).

Participants underwent a battery of neuropsychological tests to assess their language and cognitive abilities. In addition of the MoCA test (Nasreddine et al., 2005), the battery also included the object decision subtest of the Birmingham Object Recognition Battery (BORB; St-Hilaire et al., 2018) to assess visuo-perceptual processing, and the Matrix Reasoning subtest of the Wechsler Adult Intelligence Scale (WAIS-IV; Wechsler, 2011) for visual information processing and reasoning by analogy. Following the neuropsychological assessments, participant completed a language battery, including the Action Naming Test with Videos (T-DAV; Spigarelli and Wilson, 2022), which assesses action naming abilities with 20 action videos (10 high-frequency (HF) and 10 low-frequency (LF) actions). The Verb Fluency Test (Macoir and Hudon, 2023) evaluated participants' lexical access and executive functions by generating as many verbs as possible in 1 min.

Sociodemographic and pre-test assessment data of the two groups are reported in Table 1. Participants in both iTBS and placebo iTBS conditions were comparable in terms of age ($t(34) = 1.01$, $p = .319$), level of education ($t(34) = 1.09$, $p = .285$), and gender ($\chi^2(1) = .11$, $p = .738$). The two groups obtained comparable scores in the T-DAV ($t(34) = 1.68$, $p = .102$), the verb fluency test ($t(34) = 1.20$, $p = .238$), the MoCA ($t(34) = 1.04$, $p = .307$, the Matrix Reasoning subtest of the WAIS-IV ($t(34) = 1.19$, $p = .240$), visuo-perceptual processing assessed by the object decision subtest of the BORB ($t(34) = 0.94$, $p = .355$) and response latency in the experimental task ($t(34) = 1.92$, $p = .175$).

All participants were recruited at *Université Laval*. The study was approved by the *Comité d'éthique de la recherche sectoriel en réadaptation et intégration sociale du CIUSSS de la Capitale-Nationale (Projet #2023–2727)*. All participants gave their written informed consent to participate.

2.2. Study design

The experimental design is shown in Fig. 1. The study was divided into four separate sessions. The first session began with an initial remote

Table 1
Participant sociodemographic data included in the study.

	iTBS Mean (SD)	Placebo iTBS Mean (SD)	p-value
Age	27.22 (3.13)	25.89 (4.63)	.319
Education level	17.67 (1.88)	17.06 (1.47)	.285
Laterality	9.28 (.75)	9.17 (.80)	.671
MOCA	28.89 (1.13)	28.44 (1.42)	.307
Matrix Reasoning Subtest of WAIS	22.83 (1.95)	22.00 (2.22)	.240
Object Decision Subtest of BORB	26.94 (2.18)	26.28 (2.08)	.355
Fluency	27.06 (5.43)	25.11 (4.21)	.238
T-DAV	18.72 (1.36)	17.89 (1.60)	.102

Notes. Age: age in years; Education level: formal education in years. BORB: The object decision subtest of Birmingham Object Recognition Battery (St-Hilaire et al., 2018); Laterality: The Edinburgh Handedness Inventory (Oldfield, 1971); MoCA: Montreal Cognitive Assessment (Nasreddine et al., 2005); T-DAV: Action Naming Test with Videos (Spigarelli and Wilson, 2022); WAIS-IV: Wechsler Adult Intelligence Scale - Matrix Reasoning subtest (Wechsler, 2011).

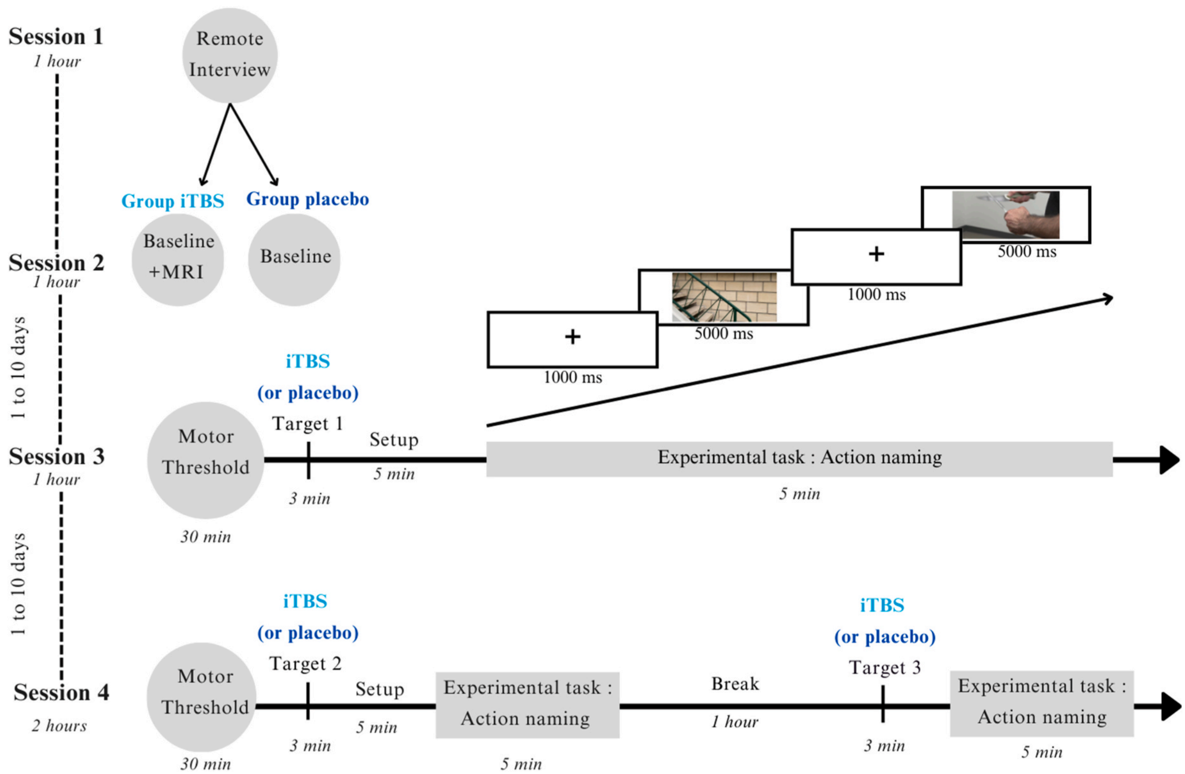

Fig. 1. Experimental design.

interview to assess participants' eligibility based on the inclusion criteria. In the second session, we obtained the baseline measures for the study. Additionally, the group of participants receiving active iTBS also underwent an MRI scan. The third session involved the administration of the iTBS protocol to one of the three selected targets. Lastly, during the fourth session, the iTBS protocol was administered to the remaining two selected targets. Stimulations of the last two targets were separated by a 1-h break to avoid potential carry-over effects (Brisson and Tremblay, 2021). This scheduling also aimed to reduce participant attrition by limiting the total number of sessions. The third and fourth sessions were conducted with intervals ranging from 1 to 10 days. The order of the targets for stimulation was randomized across participants using the six possible combinations ($3! = 6$) and counterbalanced such that an equal number of participants were assigned to each order. This approach helped control for potential fatigue and carry-over effects.

2.3. Experimental task procedure

2.3.1. Baseline measurement

Participants performed an oral action-naming task. They were seated approximately 30 cm from a computer screen, in a quiet, sound-attenuated room. Participants were instructed to name as quickly and accurately as possible 110 action clips (Bonin et al., 2009) which served as the primary outcome for our investigation. The instructions were given orally. Before beginning the task, participants were presented with three practice trials to familiarize themselves with the procedure. The experimenter emphasized the importance of responding as quickly and accurately as possible. If participants did not recognize the action depicted in a video, they were instructed to either remain silent or say "I don't know". Each trial began with the fixation cross (+) in the center of the screen for 1000 ms, followed by a 5000 ms action video. The baseline naming task lasted approximately 15 min.

The primary dependent variable in our study was response latency, measured in milliseconds (ms). Additionally, response accuracy, scored as either 1 point (correct) or 0 points (incorrect) was also considered as a dependent variable. For example, one point was given for the action "*knitting*", whereas zero points were awarded if the participant provided a periphrase such as "*she is making a scarf*".

All stimuli were presented on a computer screen using a Python script (Chauvette, 2023). This allowed precise control over stimulus presentation timing and facilitated the recording of response latency (i.e., the onset of the oral response) and the actual response itself in a.wav file. Participants' oral responses were directly recorded using the built-in microphone of a laptop (MacBook Pro 2021). The analysis of oral production onset times was conducted using Chronset (Roux et al., 2017), a fully automated system that estimates the onset of oral production based on several acoustic features. To ensure accuracy, each onset time provided by Chronset was manually verified using a Praat script (Check Voice Onset Times) (Scherpenberg et al., 2020).

2.3.2. Creation of action naming lists for iTBS sessions

To structure the experiment across stimulation sessions, we created three lists of 34 videos for each participant, based on the responses to the 110 action clips. After each iTBS session, participants performed the action-naming task using one of the three video lists. The three lists were carefully matched for frequency, length in number of phonemes, number of phonological neighbors, imageability, score and response latency for the videos (all $ps > .85$). The values for the psycholinguistic variables were taken from Lexique.org (New et al., 2004) and a database for imageability (Grégoire et al., 2024). The videos created by Bonin et al. (2009) were standardized in France. The names given in Quebec to some actions may vary from those commonly used in France. To establish the expected names in Quebec French, we asked 7 healthy participants from Quebec to name the 110 videos (see Supplementary Material for the procedure). The accepted names for the action verbs along with the psycholinguistic variables can be found in Appendix A. The lists were customized for each participant. The presentation order of the lists was counterbalanced for each participant. The order of video presentation within each list was randomized.

2.4. MRI for transcranial magnetic stimulation navigation: precise anatomical targeting in TMS

The iTBS group underwent a structural MRI scan at the CERVO brain research center using a 3T Siemens Prisma MRI with a 64-channel head and neck coil. The structural images served as a precise anatomical reference for neuronavigation during the TMS procedures, enabling accurate targeting of the desired brain regions for stimulation. This approach ensured consistent and reliable targeting across all participants. High-resolution T1-weighted structural images were acquired using a rapid gradient echo 3D magnetization-prepared rapid gradient-echo (MP-RAGE) sequence. The scanning parameters were as follows: repetition time (TR) = 8.2 ms, echo time (TE) = 3.7 ms, field of view (FOV) = 250 mm, flip angle = 8°, matrix size = 256 × 256, 180 slices per volume, slice thickness = 1 mm, and no gap between slices.

2.5. Repetitive transcranial magnetic stimulation (rTMS)

We stimulated two targets involved in the neural processing of action naming, the left middle frontal gyrus (MFG; −30, 46, 33) (Koyama et al., 2017) and the left inferior frontal gyrus pars opercularis (IFGpo; −54, 12, 18) (Bulut, 2022). Based on the study by Brisson and Tremblay (2021), we added a control site, the left superior parietal lobe (SPL; −9, −69, 57). The SPL was not expected to modulate activity specifically related to action naming. Montreal Neurological Institute (MNI) coordinates were defined for each targeted region. Fig. 2 illustrates the targets of the present study.

The MNI coordinates of each region were backtransformed to each participant's native space. T1-weighted images for each participant were uploaded into the Brainsight software, which was then used to define the MRI fiducials (nasion and left and right preauricular points) and anatomical markers (anterior and posterior commissures). This process was conducted only once per participant, prior to the first stimulation session, and the file was saved and reused in the subsequent session (targets 2 and 3). For each session, the target region was mapped onto the participant's brain reconstruction using MNI coordinates that were transformed into native space. Following coil calibration, specific head placement and shape points (*i.e.* tip of nose, root of nose, ears) were determined for each participant. Subsequently, the coil was guided and securely held in place over the target region of interest using the camera and visual feedback provided by the Brainsight system.

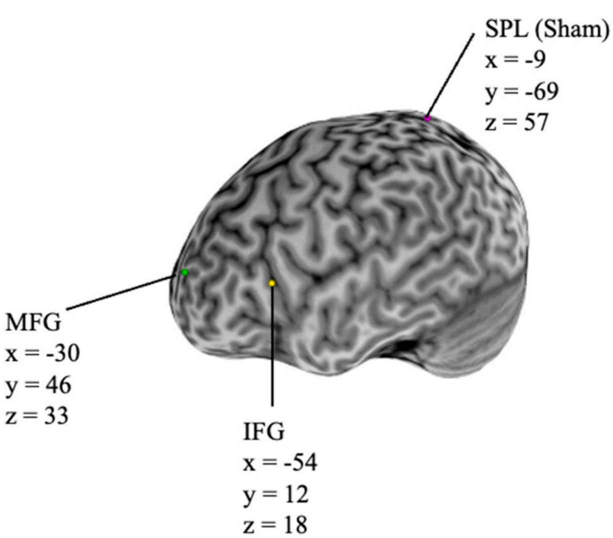

Fig. 2. Targets of the present study with their corresponding MNI Coordinates *Notes*. IFG: Inferior Frontal Gyrus, MFG: Middle Frontal Gyrus, SPL: Superior Parietal Lobule. The coordinates provided are in Montreal Neurological Institute (MNI) space.

2.5.1. Stimulation protocol

For each participant, the optimal stimulation position ("hotspot") and active motor threshold was first determined using single-pulse TMS. This motor threshold was used to calculate the appropriate stimulation intensity for iTBS. The active motor threshold was determined by gradually increasing the intensity of TMS over the primary motor cortex. The average intensity was 45.31 ± 4.20 (range: 38–53). This procedure continued until at least five motor evoked potentials (MEPs) out of ten trials were generated, with an amplitude of ≥200 μV. Participants were instructed to maintain a slight voluntary contraction of the target muscle. The parameters for iTBS were based on the protocol by Brisson and Tremblay (2021). The head was immobilized manually, and coil displacements were limited. Trains of three rapid pulses, presented at 50 Hz and repeated at a frequency of 5 Hz for 2 s, with an intertrain interval of 10 s, were delivered for a total of 190 s (equivalent to 600 pulses). The stimulation intensity was set at 80 % of the individual active motor threshold (Rossi et al., 2021).

2.5.2. Repetitive transcranial magnetic stimulation sessions

The first target was stimulated at the 3rd session, whereas the second and third targets were stimulated at the 4th session (see Fig. 1). The oral naming task was administered 5 min after the iTBS session and lasted approximately 5 min. This 5-min interval allowed participants to transition from the stimulation seat to the oral naming task station, to sit comfortably and to be reminded of the task instructions. The oral naming task was performed within a window for which the effects of iTBS are known to be optimal, from the end of stimulation until around 20 and 30 min after iTBS (Gedankien et al., 2017; Huang et al., 2005). The procedure and instructions were identical to those given during the baseline session. Participants were informed that the task would last approximately 5 min and that a blank screen would appear at the end of the task. No additional examples or practice trials were given, as participants had already familiarized themselves with the task during the baseline phase.

At the 4th session, the remaining two brain targets were stimulated. After stimulation of the second target, the participant was asked to name a second list of action videos. Following the naming task, an hour-long break was provided to ensure the return of excitability to the resting state between each target and to avoid potential cumulative effects (Huang et al., 2005). This interval duration was chosen based on previous studies showing that the effects of iTBS typically peak within 20–30 min post-stimulation and tend to dissipate thereafter (Chung et al., 2016; Wischnewski et al., 2015).

During this break, the participant was encouraged to engage in activities like walking. After the break, the third target was stimulated. Following brain stimulation of the third target, the participant named the third list of videos of actions.

Placebo Group. The placebo iTBS group underwent the same procedure as the iTBS group of healthy participants with the only difference being that they received only placebo iTBS. The placebo stimulation involved a sham stimulation performed by a dummy 8-shaped coil, mimicking the sound and scalp contact of the active stimulation. The brain coil was positioned on the participant's head using a brain reconstruction in the Brainsight software, based on another participant's data. Thus, the coil was placed over similar targets as in active iTBS: the left IFGpo, the left MFG, and the left SPL. Participants were unaware that the stimulation was fictitious.

3. Statistical analysis

For response latencies (RLs), we used a linear mixed-effects model with RLs as the dependent variable and group (iTBS versus placebo iTBS), time of measurement (pre- and post-test) and targets (left IFGpo, left MFG and left SPL), and their interactions as fixed factors, and items and participants as random factors. These results were derived using the Satterthwaite method for degrees of freedom. For the score, we ran a mixed logistic model with group, time of measurement, and targets as fixed factors and items and participants as random factors. In case of significant interactions, simple effects were run. When the main effect of target was significant, Bonferroni post-hoc tests with corrected p-values were conducted. We report exponentiated coefficients (exp(B)), also known as odds ratios, which indicate the predicted change in odds for a one-unit increase in the predictor. All analyses were run with JAMOVI (https://www.jamovi.org, The jamovi project, 2024).

4. Results

4.1. Response latencies (RLs)

The effect of group did not reach significance, $F(1, 33.9) = 1.92$, $p = .175$. The time of measurement significantly affected performance, $F(1, 5956.2) = 507.18$, $p < .001$. RLs were faster in the post-test ($M = 1308$ ms, $SD = 558$) as compared to the pre-test ($M = 1591$ ms, $SD = 682$), regardless of the group or target. The target did not reach significance, $F(2, 5979.1) = .36$, $p = .695$. The interaction group x time of measurement was significant, $F(1, 5955.4) = 6.89$, $p < .01$. Simple effects for the iTBS group showed a significant effect of time of measurement, $F(1, 3010) = 270.82$, $p < .001$. Simple effects for the placebo iTBS group showed a significant effect of time of measurement, $F(1, 2845) = 243.28$, $p < .001$. The reduction in RLs was larger for the iTBS group (iTBS difference: 324.2 ms), as compared to placebo iTBS (placebo iTBS difference: 256.6 ms; mean difference iTBS versus placebo: 67.6 ms) (see Fig. 3). There were no significant effects of group x target, $F(2, 5975.3) = .07$, $p = .931$. The interaction time of measurement x target was not significant, $F(2, 5955.4) = .05$, $p = .954$. The interaction group x time of measurement x target, $F(2, 5954.9) = 1.27$, $p = .280$, did not reach significance.

4.2. Scores

The effect of group was significant, $X^2(1) = 7.73$, p = .005. The iTBS group (M = .87, SD = .34) showed higher scores as compared to the placebo group (M = .82, SD = .38). Time of measurement significantly affected scores, $X^2(1) = 9.72$, p = .002. The scores at post-test were significantly higher than those at pre-test (Mean at pre-test = .82, SD = .38, mean at post-test = .84, SD = .36). The effect of target was significant, X^2 (2) = 6.75, p = .034. Bonferroni post-hoc comparisons showed a statistically significant difference between the IFGpo and the MFG, exp (B) = 1.26, z = 2.52, p = .035. Since participants in the placebo iTBS condition did not receive active iTBS, we ran the post-hoc comparisons by group separately, collapsing pre- and post-test. For the placebo iTBS, the difference in accuracy between the IFGpo (M = .82, SD = .38) and the MFG (M = .82, SD = .38) was .002. For the iTBS group, the difference in accuracy between the IFGpo (M = .88, SD = .32) and the MFG (M = .85, SD = .35) was .023. The mean score for the IFGpo was 2.3 % superior to that of the MFG. The comparisons between the IFGpo and the SPL, exp(B) = 1.07, z = .77, p = 1.000, and between the MFG and the SPL, exp(B) = .85, z = −1.77, p = .230, were not significant. Fig. 4 illustrates the pre- and post-means categorized by target. The interactions group x time of measurement, X^2 (1) = .42, p = .518, group x target, X^2 (2) = .35, p = .837, and time of measurement x target, X^2 (2) = .77, p = .679, did not reach significance. The triple interaction group x time of measurement x target, X^2 (2) = .87, p = .648, was not significant.

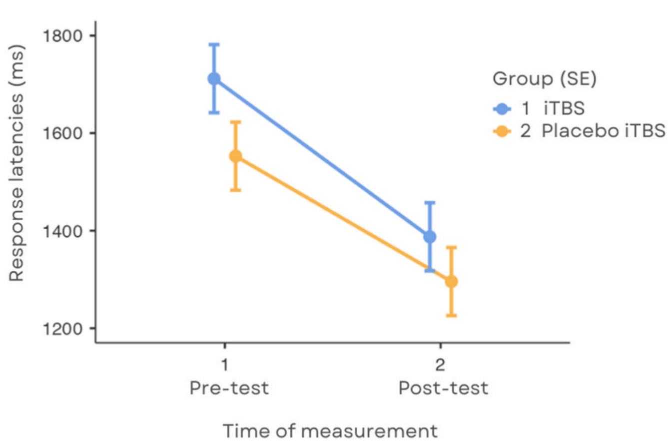

Fig. 3. Comparison of mean differences between pre-test and post-test for iTBS and Placebo iTBS groups.

5. Discussion

The objective of the present study was to determine whether the neural network involved in naming actions from videos was comparable to that involved in naming actions from pictures. To this end, we targeted the left IFGpo and the left MFG, two brain regions known to be involved in picture action naming. The RLs were comparable between the iTBS and placebo iTBS groups. However, RLs were modulated by the type of intervention. The iTBS group showed a greater improvement in RLs before/after the iTBS intervention, as compared to the placebo group. This improvement cannot solely be attributed to a learning effect from re-exposure to the stimuli, as the iTBS group showed a greater reduction in RLs. These results demonstrate that iTBS stimulation modulates and improves the speed of action naming when using videos stimuli. This finding is consistent with previous research demonstrating reduced RLs for picture action naming following rTMS stimulation in healthy individuals (Bolgina et al., 2022; Cappa et al., 2002; Cotelli et al., 2010). Thus, our results reproduce – and extend to video action naming – what has previously been found for picture action naming.

The iTBS group had higher scores compared to the placebo group. Both groups showed improvements in video action naming accuracy after the intervention, irrespective of whether they belonged to the iTBS or the placebo iTBS groups. In other words, our results show that iTBS did not specifically affect naming accuracy. This is in contrast with previous research. Bolgina et al. (2022) demonstrated better picture action naming following rTMS stimulation of the left IFG compared to a sham condition. In their study, each participant was stimulated in three targets and a sham condition where rTMS did not deliver any pulses. Unlike the present study, in Bolgina et al. (2022) there was no control group. The presence of a control group in our study allowed us to determine whether the observed effects were due to the iTBS intervention or other confounding factors. Another difference between the present study and that of Bolgina and colleagues is the absence of a baseline in the latter (i.e., a pre-intervention condition). Both the control group and the baseline measure allowed us to control for confounding effects, such as the implicit learning that might take place after the second presentation of the video naming stimuli. We argue that these differences made our study more robust. These substantial methodological differences may, at least partially, account for the differences found between our study and that of Bolgina and colleagues. Given our young and healthy participant group, our results may be attributed to a ceiling effect due to their high initial baseline level. Some studies have shown that the lower a person's baseline performance, the more TMS improves it (e.g., Brisson and Tremblay, 2021). Future studies should determine the effect of iTBS on video action naming in populations likely to experience improvement, such as those with primary progressive aphasia or post-stroke aphasia. In fact, the efficacy of rTMS on naming accuracy has already been demonstrated in such patients (Arheix-Parras et al., 2021; Kielar et al., 2022; Spigarelli et al., 2024; Yao et al., 2020). This study could also be replicated with older adults or individuals with lower baseline performance to better understand the potential benefits of iTBS in these groups.

Finally, we targeted two specific brain regions identified as part of the network involved in picture action naming to investigate whether

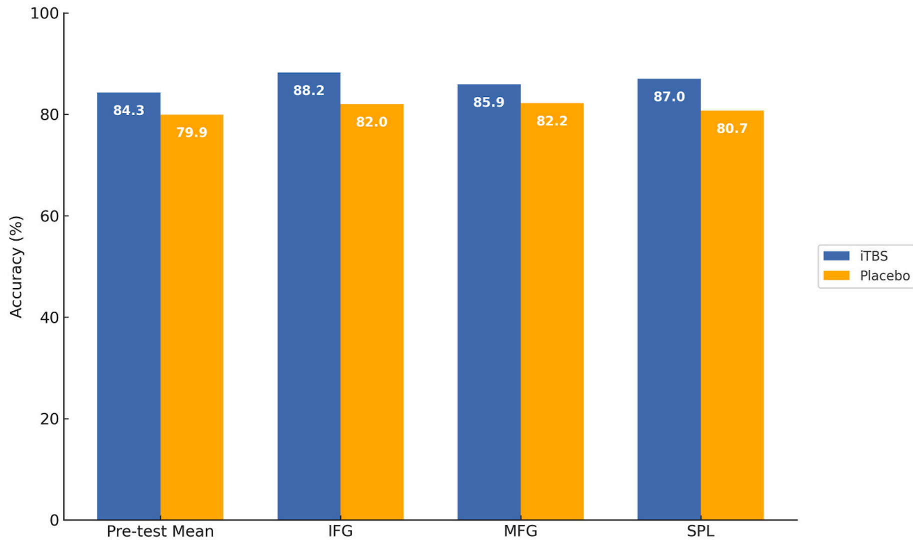

Fig. 4. Action naming accuracy (in %) between pre- and post-Test for iTBS and placebo iTBS
Notes. IFG: Inferior Frontal Gyrus, MFG: Middle Frontal Gyrus, SPL: Superior Parietal.

these same regions are also specific to video action naming. The target did not modulate RLs. The performance improvements were comparable across all three targets. This indicates that the benefits of iTBS were not region-specific in our study. Contrary to RLs, the target did modulate video action naming scores. More precisely, higher naming scores were associated with left IFGpo stimulation as compared to the MFG in the iTBS group. The left IFG is well-established for its involvement in picture naming, including nouns and verbs (Alves et al., 2023; Vigliocco et al., 2011). Neuroimaging investigations have revealed distinct functional roles for the left IFG. Specifically, the posterior portion (i.e. pars opercularis) is implicated in syntactic aspects of language comprehension and production (Caplan et al., 1998; Ishkhanyan et al., 2020; Klaus and Hartwigsen, 2019). This brain region has been prominently targeted in studies employing rTMS among healthy individuals as well as those with acquired language disorders such as post-stroke aphasia (see Arheix-Parras et al., 2021; Klaus and Schutter, 2018, for a comprehensive literature review). Our study highlights that the IFGpo also appears to be involved in video action naming. These findings suggest that the IFGpo plays an important role not only in naming static images but also in naming actions depicted in videos. The stimulation of the left MFG also led to improved video action naming accuracy, albeit to a lesser degree than the left IFG. Recent studies have demonstrated the effectiveness of rTMS in modulating the excitability of circuits in the dorsolateral prefrontal cortex (dlPFC), thereby facilitating naming processes (Cappa et al., 2002; Cotelli et al., 2006, 2010, 2012). From a neuroanatomical perspective, the dlPFC is located in the MFG. Our results highlight the involvement of the left MFG in the neural network that underlies video action naming. In sum, the two target areas of our study, the left IFGpo and the left MFG, known to be involved in picture action naming, are also implicated in video action naming. However, the left IFG appears to play a more predominant role compared to the left MFG.

Finally, following previous literature (Brisson and Tremblay, 2021), we selected the left SPL as a control site. Thus, we did not predict any effects of the left SPL stimulation on action naming. Conversely, our results show that the left SPL stimulation improved naming accuracy. This result might be explained by the fact that the left SPL plays a multifaceted role in integrating somatosensory and visuospatial information, while also contributing to functions such as attention, emotion regulation, written language, and working memory (Briggs et al., 2020; Schmahmann et al., 2008). Watching action videos might therefore incur a more significant attentional cost as compared to pictures. Therefore, it is plausible that the stimulation of the left SPL could modulate video action naming scores particularly due to its prominent role in visual attention. This raises the question of whether the stronger visual component of videos engages the SPL more than pictures. Further studies are needed to elucidate the precise role of the left SPL in video action naming.

5.1. Limitations

This study presents a few limitations. Firstly, the examiner was not blinded to the stimulation group (iTBS versus placebo). This might have introduced some biases. Indeed, all stimulations were administered by the principal author (MS). The use of a blinded examiner to administer the stimulations would have reduced this potential bias.

We chose to administer stimulation to one target on a separate day, while the remaining two targets were stimulated on the same day. This decision was made to minimize participant attrition, as adding a fourth testing session could have increased the likelihood of dropouts. We acknowledge, however, that this approach may have introduced greater participant fatigue as well as carry-over effects. Nonetheless, we believe that the inclusion of a 1-h break between sessions, the short duration of the task and the counterbalanced target order helped mitigate the potential impact of fatigue and carry-over effects on the performance.

Moreover, we chose the left SPL as a control site based on previous literature (Brisson and Tremblay, 2021). However, it is important to note that this region is also implicated in higher-order cognitive processes. A more neutral region might have been a more suitable choice as a control site (e.g., vertex (Harvey et al., 2019; Klaus and Hartwigsen, 2019)) to avoid potential confounding effects and should be considered in future studies. Additionally, it is worth noting that the sample size is relatively small, with fewer than 20 participants per group. This limited sample size may reduce the generalizability of our findings. Our sample included only young, healthy adults, whose neural and plasticity profiles likely differ from those of older or language-impaired individuals. As such, the clinical relevance of these findings remains uncertain and should be interpreted with caution. Future studies involving older adults or individuals with language impairment are needed to determine whether these findings generalize to clinical populations.

6. Conclusion

This study highlighted the direct involvement of the left IFGpo, the left MFG, and the left SPL in video action naming. The iTBS group elicited greater improvement in RLs compared to the placebo group after the intervention. In terms of accuracy, both groups showed improved action naming post-iTBS, but the improvement in video naming score was greater in the iTBS group after stimulation of left IFGpo as compared to the left MFG. This is the first study to address the brain network for video action naming in healthy participants. Further studies in both healthy and clinical populations, such as post-stroke aphasia, are needed to better identify the brain network associated with video action naming.

CRediT authorship contribution statement

Manon Spigarelli: Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Hugo Massé-Alarie:** Writing – review & editing, Supervision, Methodology, Formal analysis, Conceptualization. **Pascale Tremblay:** Writing – review & editing, Conceptualization. **Maximiliano A. Wilson:** Writing – review & editing, Validation, Supervision, Methodology, Formal analysis, Conceptualization.

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Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2025.109221.

Appendix A

Inventory of Action Verbs and Psycholinguistic Variables

Action verb (in French)	English translation	Imageability	Lexical frequency	Number of letters	Number of phonemes	Syllabes count	Number of phonological neighbors
aboyer	to bark	6.05	2.72	6	6	3	6
accrocher	to hang	5.5	5.84	9	6	3	5
allumer	to light up	5.4	6.36	7	5	3	7
appeler	to call	5.9	6.56	7	5	3	7
applaudir	to applaud	6.9	5.04	9	7	3	2
arroser	to water	6.35	5.84	7	5	3	7
asperger	to spray	5.05	2.04	8	7	3	3
aspirer	to vacuum	3.5	3.36	7	6	3	5
attacher	to tie	6.9	6.36	8	5	3	7
attraper	to catch	6.05	6.16	8	6	3	5
bâiller	to yawn	6.4	5.56	7	4	2	23
balayer	to sweep	6.25	4.8	7	5	3	3
barrer	to lock	5.5	6.12	6	4	2	29
boire	to drink	6.65	6.88	5	4	1	14
brancher	to plug in	5.6	5.64	8	5	2	10
brasser	to stir	5.95	5.48	7	5	2	11
calculer	to calculate	4.9	5.6	8	7	3	4
chanter	to sing	6.1	6.32	7	4	2	17
chuchoter	to whisper	5.5	4.72	9	6	3	4
claquer	to snap	5.25	3.16	7	5	2	12
clouer	to nail	6.8	4.32	6	4	2	6
cogner	to knock	6	5.44	6	4	2	11
coller	to glue	5.75	5.88	6	4	2	22
compter	to count	4.5	6	7	4	2	20
conduire	to drive	6.65	6.52	8	6	2	2
coudre	to sew	5.95	4.24	6	4	1	6
couler	to flow	4.35	4.96	6	4	2	23
couper	to cut	6.3	6.52	6	4	2	18
courir	to run	6.75	6.64	6	4	2	9
creuser	to dig	6.3	5	7	5	2	5
cueillir	to pick	5.75	4.32	8	4	2	3
décalquer	to trace	2.5	1.6	9	7	3	2
découper	to cut out	6.25	5.24	8	6	3	8
dégoutter	to drip	4.45	4.48	9	6	3	7
descendre	to descend	5.4	6.72	9	6	2	11
dessiner	to draw	6.5	5.52	8	6	3	8
distribuer	to distribute	4.15	4.48	10	8	3	5
donner	to give	6.5	4.96	6	4	2	14
écouter	to listen	4.7	6.8	7	5	3	8
écraser	to crush	5.9	4.52	7	6	3	4
écrire	to write	6.45	6.92	6	5	2	3
effacer	to erase	6.15	6.16	7	5	3	5
embrasser	to kiss	6.6	5.76	9	6	3	7
éplucher	to peel	6.2	4.76	8	6	3	4

(*continued on next page*)

(*continued*)

Action verb (in French)	English translation	Imageability	Lexical frequency	Number of letters	Number of phonemes	Syllabes count	Number of phonological neighbors
essuyer	to wipe	5.7	5.96	7	6	3	4
éternuer	to sneeze	6.25	4.6	8	6	3	4
étrangler	to strangle	6.4	3.24	9	7	3	3
faire	to do	6.8	6	5	3	1	28
faucher	to mow	3.9	1.76	7	4	2	15
fermer	to close	5.45	6.88	6	5	2	9
filmer	to film	6.15	5.36	6	5	2	5
frapper	to hit	6.3	5.56	7	5	2	7
fumer	to smoke	6.75	5.2	5	4	2	9
glisser	to slip	6.1	5.4	7	5	2	8
gonfler	to inflate	5.5	4.24	7	5	2	4
goutter	to taste	2.7	3.2	7	4	2	20
grimper	to climb	6	5.04	7	5	2	8
indiquer	to indicate	3.7	3.84	8	5	3	5
japper	to yap	6.15	5.48	6	4	2	16
jeter	to throw	5.65	6.36	5	4	2	8
jogger	to jog	6.5	3.96	6	5	2	0
lacer	to lace	5.95	2.84	5	4	2	22
lécher	to lick	6.2	3.36	6	4	2	18
licher	to lick	6.4	4.88	6	4	2	19
lire	to read	6.6	6.88	4	3	1	32
manger	to eat	6.7	7	6	4	2	12
marcher	to walk	6.7	6.84	7	5	2	8
méditer	to meditate	5.35	4.04	7	6	3	6
mélanger	to mix	5.75	5.68	8	6	3	4
mesurer	to measure	5.9	5.64	7	6	3	4
montrer	to show	5.3	6.56	7	5	2	8
mordre	to bite	6.6	4.92	6	5	1	7
neiger	to snow	6.3	6.32	6	4	2	5
offrir	to offer	4.35	4.44	6	4	2	0
ouvrir	to open	5.5	6.8	6	5	2	4
parler	to talk	6.2	6.92	6	5	2	8
passer	to pass by	6.6	4.68	6	4	2	27
payer	to pay	5.95	6.84	5	3	2	19
pêcher	to fish	6.6	4.92	6	4	2	19
pédaler	to pedal	6.6	4.8	7	6	3	4
peigner	to comb	6.4	4.92	7	3	2	13
peindre	to paint	6.5	3.72	7	3	1	10
pelleter	to shovel	6.6	6.04	8	6	3	2
peser	to weigh	5.3	5.16	5	4	2	7
pincer	to pinch	5.9	3.8	6	4	2	13
plier	to fold	6.15	6.08	5	5	2	7
pointer	to point	6	5.12	7	5	2	7
poster	to post	4.85	3.76	6	5	2	7
presser	to squeeze	3.9	3.16	7	5	2	8
prier	to pray	5.85	4.04	5	5	2	14
racler	to scrape	4.8	3	6	5	2	8
ratisser	to rake	3.15	1.92	8	6	3	8
refuser	to refuse	3.5	5.52	7	5	3	5
regarder	to look	4.45	6.8	8	7	3	5
remuer	to stir	4.75	2.68	6	5	2	6
repasser	to iron	6.2	4.6	8	6	3	12
sauter	to jump	6.45	5.96	6	4	2	22
scier	to saw	6.75	3.92	5	3	1	18
scruter	to scrutinize	3.6	1.96	7	6	2	5
sculpter	to carve	6.1	3.08	8	6	2	4
semer	to sow	5.45	3.84	5	4	2	8
siffler	to whistle	5.95	4.76	7	5	2	8
signer	to sign	5.85	5.48	6	4	2	14
sonner	to ring	5.7	5.32	6	4	2	15
souffler	to blow	6.15	4.96	8	5	2	6
sourire	to smile	6.9	6.2	7	5	2	10
squatter	to squat	4.35	3.72	8	6	2	1
suspendre	to suspend	4.9	4.2	9	7	2	6
tailler	to carve	4.95	3.36	7	4	2	24
téléphoner	to call	6.8	5.96	10	8	4	6
tirer	to shoot	5.6	5.48	5	4	2	25
tondre	to cut	6.1	4.48	6	4	1	9
trancher	to slice	5.65	4.72	8	5	2	10
tremper	to dip	4.85	4.52	7	5	2	7
tricoter	to knit	6.75	3.88	8	7	3	5
vaporiser	to spray	5.35	3.12	9	8	4	4
verser	to pour	5.95	5.24	6	5	2	13
viser	to aim	5	4.24	5	4	2	16
visser	to screw	6.5	4.76	6	4	2	14

(*continued on next page*)

(*continued*)

Action verb (in French)	English translation	Imageability	Lexical frequency	Number of letters	Number of phonemes	Syllabes count	Number of phonological neighbors
Atchoumer	to sneeze	6.35	5.72	9	6	3	
Dégrimper	to climb down	1.8	1.16	9	7	3	
Jaser	to chatter	5.3	5.96	5	4	2	
Maller	to post	4.6	2.92	6	4	2	
Peinturer	to paint	6.6	5.16	9	6	3	
Pluguer	to plug	4.55	4.68	7	5	2	
Puisher	to spray	3.05	2	7	4	2	
S'accroupir	to squat	5.45	2.4	9	6	3	
S'agenouillr	to kneel	6.45	2.64	11	7	4	
S'étirer	to stretch	6.35	5.72	6	5	3	
Saluer	to greet	6.45	5.44	6	5	3	
Se balancer	to swing	5.9	4.68	8	6	3	
Se gratter	to scratch	6.55	6.08	7	5	2	
Se laver	to wash	6.6	6.88	5	4	2	
Se peigner	to comb	6.45	5.2	7	3	2	
Se peser	to weigh	6.3	5.28	5	4	2	
Se raser	to shave	6.65	5.68	5	4	2	
Sprayer	to spray	3	1.6	7	6	2	

Notes. Imageability was calculated using the database of Grégoire et al. (2024) and the collected norms, while lexical frequency was computed using the Lexique.org database (New et al., 2004) and the gathered norms. The counts for letters, phonemes, syllables, and phonological neighbors were obtained from Lexique.org (New et al., 2004).

Data availability

Data will be made available on request.

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