Dissociating language and thought in human reasoning

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Abstract

What is the relationship between natural language and complex thought? In the context of complex reasoning, there are two main views on this question. Under the first, language sits at the center of the ability to process the syntax-like combinatorial operations necessary for various forms of complex reasoning, such as deductive reasoning. Under the second, these operations are independent of the mechanisms of natural language. We used noninvasive brain stimulation to assess the effects of transient inhibition of neural activity in targeted neural systems. If language and deductive reasoning can be shown to be dissociable with this approach, then the hypothesis that language is crucial to deductive reasoning can be ruled out. We inhibited Broca's area, a region associated in prior research with parsing the syntactic relations of natural language, and dorsomesial frontal cortex, a region previously described as core for logic reasoning. We tested the effects of perturbing activity in these areas on processing the syntactic operations of natural language and the syntax-like operations of deductive logic. The dissociative hypothesis of language and deductive reasoning predicts an interaction between stimulated areas and tested functions, which we observed. This interaction demonstrates that the effects of brain perturbation are reliably different at the two stimulated sites (Broca's area and dorsomesial prefrontal cortex) and for the two functional processes (language and thought). Transient inhibition of Broca's area disrupted linguistic processing without affecting deductive reasoning, whereas transient inhibition of dorsomesial frontal cortex exhibited the reverse pattern, albeit to a lesser degree. These results are evidence for the independence of abstract complex reasoning from natural language, at least in the adult brain. (236 words)

Author summary

Whether complex cognition is enabled by or founded upon the mechanisms of natural language has long been debated in many fields, including philosophy, psychology, and, more recently, neuroscience. In the context of human reasoning, some view language as central to inference-making, while others view this ability as independent of the mechanisms of natural language. Using a neuromodulatory approach, we show that it is possible to disrupt the neural mechanisms of natural language without affecting reasoning and *vice versa*. This result provides the first causal evidence that in the adult brain logic reasoning is independent of the mechanisms of natural language.

Introduction

Does language shape human cognition [1–5]? This question is generally framed within two opposite positions: the communicative conception of language, in which language is viewed primarily as an inert means of communicating preexisting (i.e., non-linguistic) mental representations from one mind to another through a mutually intelligible code, and the cognitive conception of language, in which language is viewed as constitutively involved in human cognition and the medium of thought [6].

A useful empirical approach to investigating this question is to look at neural systems associated with these functions. For instance, some view Broca's area, in the left inferior frontal gyrus (IFG), a brain region typically associated with processing the hierarchical sequences of natural language [7–9], as containing a mechanism for processing hierarchical sequences across domains of human thought [10–12].

In the context of human reasoning, it has long been debated whether language plays a role in deductive inference-making [13–17], and a growing body of neuroimaging work has renewed the debate between the two contrasting positions [18–22]. Under one view, the syntax-like operations of deductive reasoning are mainly based upon the neural mechanisms of language, in the left IFG [23, 24], and thus best understood as linguistic in nature (henceforth the "language-centric" view of deduction). Under the other view, deductive reasoning is mainly supported by neural mechanisms extending beyond the conventional "linguistic" regions of the brain (cf., [25] for discussion), spanning left dorsomesial frontal and frontopolar cortices (in Brodmann areas [BA] 8 and 10, respectively [26–28]; henceforth the "language-independent" view of deduction). Of course, under this latter view, it is understood that linguistic resources might first be necessary to decode verbally presented logic statements into mental representations. However, beyond allowing for the transformation of verbal input into mental representations, the linguistic structures of the left IFG are considered to play no role in the mental operations of deductive inference-making [20, 26, 29].

In order to further test these two positions, we took a step beyond correlational neuroimaging evidence and used noninvasive brain stimulation, an empirical approach that allowed us to investigate causal links between specific brain regions, cognition, and behavior [30, 31]. Noninvasive brain stimulation makes it possible to transiently disrupt (or enhance) neural activity in targeted systems. If this approach showed dissociable functional effects between language and reasoning, the "language-centric" view of deduction could be ruled out.

As shown in Fig. 1a,b, we adopted an experimental design including two sites of interest (Broca's area, historically associated with language, and dorsomesial frontal cortex, associated with deductive inference [25–28]), and two tasks of interest (linguistic reasoning, logic reasoning; cf., Table S1). We also added a "control" site (left transverse occipital sulcus; LTOS), to control for nonspecific effects of brain stimulation, as well as a "control" task, to control for unanticipated impairments in relevant functional processes like grammar (all adapted from previous work [25]; see Materials and Methods). In each of three sessions, participants performed all three tasks before and after continuous theta burst stimulation (cTBS), which transiently inhibits brain activity in a localized area for close to 60 minutes [30], allowing for a careful testing of functional impairments. Only one site was stimulated per session, with a counterbalanced order across participants (see Supplementary Material). We also note that, for each task, half the trials included statements concerning the relationships between three variables (e.g., "X was given Y by Z." and "If either X or Y then not Z.") and the remainder included statements concerning the relationship between 4 variables (e.g., "W heard that Z was seen by Y taking X." and "If either Z or W then both X and not Y."). This was done to test for potential effects of cTBS on working memory functions. However, since we found no significant main effect for the number of variables, no significant 2-way interaction with either site or task, and no significant 3-way interaction (all ps > 0.05; see discussion), we omit this variable from the results reported below.

Results

Table 1 summarizes the accuracies for each stimulation site and experimental condition. We first tested the dissociative hypothesis with a 2 × 2 within-subjects ANOVA and then expanded the analysis to the control site and task (in a 3 × 3 design; henceforth, "full analysis").

Table 1. Percent accuracy for each task before (Pre) and after (Post) transient inhibitory stimulation to each site.

	Stimulation site					
	Broca's Area		**Mesial BA8**		**LTOS**	
	Pre	*Post*	*Pre*	*Post*	*Pre*	*Post*
Linguistic reas.	91%	83%	78%	81%	80%	80%
Logic reas.	70%	75%	75%	73%	67%	76%
Grammatic. judgm.	89%	82%	82%	84%	77%	84%

Collapsing across stimulation sites and pre- and post-cTBS trials, accuracies for linguistic reasoning and grammaticality judgments were higher than for logic reasoning (83%, 84%, and 73%, respectively; see Table 1). A 2 × 2 within-subjects ANOVA over participants' post-cTBS accuracy percent change relative to pre-cTBS baseline accuracy revealed a significant interaction ($F_{1,14} = 9.67$, $p = 0.008$, $\eta_p^2 = 0.41$) between stimulation site (Broca's area versus dorsomesial BA8) and task (linguistic reasoning vs. logic reasoning) (Fig. 1c). No main effect of stimulation site ($F_{1,14}$= 0.85, $p = 0.37$, $\eta_p^2 = 0.06$) or task ($F_{1,14} = 0.74$, $p = 0.40$, $\eta_p^2 = 0.05$) was observed. This interaction demonstrates that the effect of inhibitory brain stimulation differs significantly between sites and tasks, thus revealing the dissociation between language and deductive reasoning that is incompatible with the 'language-centric' view of deduction.

We subsequenly tested the effects of cTBS at each stimulation site of the 2 × 2 ANOVA. Transient cTBS inhibition of Broca's area resulted in significantly different patterns of accuracy percent change across linguistic and logic reasoning ($t_{14} = -2.40$, $p = 0.015$). Specifically, as shown in Fig 1c, transient inhibition to Broca's area decreased accuracy for linguistic problems by 7.4%, relative to pre-cTBS baseline accuracy, while sparing logic reasoning, for which accuracy increased by 4.4% relative to pre-cTBS baseline (this increase is likely due to increased familiarity with the task, unaffected by cTBS). Transient inhibition of dorsomesial BA8 resulted in the opposite pattern (Fig. 1b), with post-cTBS accuracy for logic reasoning decreasing by 1.5% and

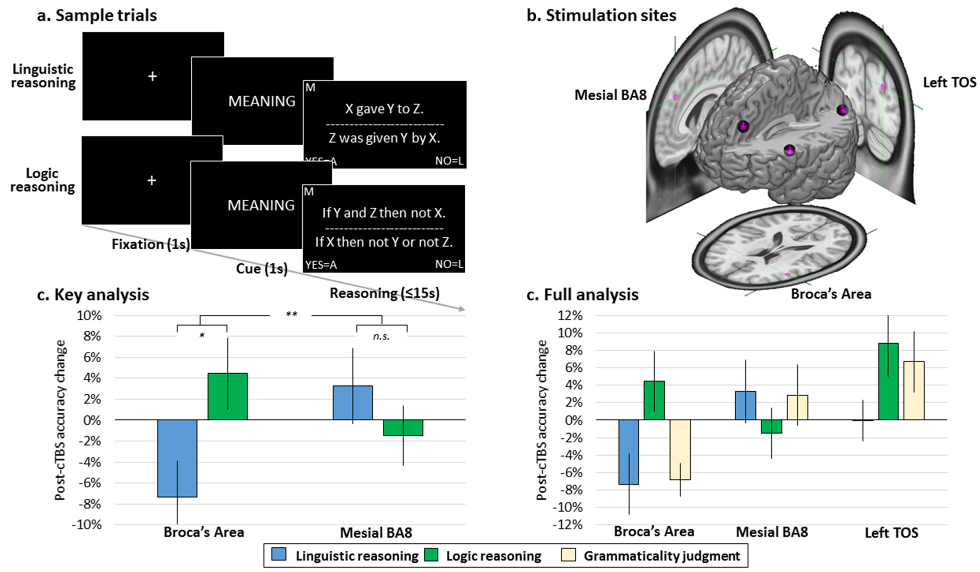

Fig 1. Experimental design and results: (a) Timeline and sample trials for a linguistic reasoning and a logic reasoning trial (see Table S1 for sample grammaticality judgment trials). (b) cTBS target sites: Broca's area (aimed at the pars opercularis of the inferior frontal gyrus; MNI coordinates: x = -50, y = 18, z = 18 [25]), mesial BA8 (MNI coord: x = -6, y = 40, z = 38 [25, 28]), and LTOS (MNI coord: x = -25, y = -85, z = 25 [32]). (c) Key analysis result: Percent accuracy change for linguistic (blue) and logic (green) reasoning after cTBS to Broca's area (left) and mesial BA8 (right). (d) Full analysis result: Percent accuracy change for linguistic (blue) and logic (green) reasoning, and grammaticality judgments (yellow) after cTBS to Broca's area (left), mesial BA8 (middle), and LTOS (right). (Error bars indicate standard error; "**" indicates p < 0.005; "*" indicates p < 0.05; "n.s." indicates non-significant effect; see text for details.).

post-cTBS accuracy for linguistic reasoning increasing by 3.3%, compared to pre-cTBS baseline. The difference, however, was not statistically significant (t_{14} = -0.99, p = 0.17). This finding, however, does not invalidate the reliability of the two-way interaction, which is the direct test of dissociability between language and thought, within our experimental design. The lack of a reliable difference of cTBS effects at the dorsomesial site likely speaks to the more distributed representation of deductive reasoning in the human cortex.

Inclusion of control stimulation site and task (grammaticality judgment) [25, 33] in a 3 × 3 within-subjects ANOVA confirmed the significant interaction of task and site ($F_{4,56} = 2.73$, $p = 0.038$, $\eta_p^2 = 0.16$) reported above. Not surprisingly, it also revealed a significant main effect of stimulation site ($F_{2,28} = 5.17$, $p = 0.012$, $\eta_p^2 = 0.27$), driven by the inclusion of the control (LTOS) site (cf., Fig. 1d). In order to further test the relationship between site and task in this 3 × 3 ANOVA, we performed trend analyses. If Broca's area is specific to linguistic processes, cTBS to this region ought to decrease accuracies for linguistic reasoning (but not for logic reasoning) more so than cTBS to either dorsomesial BA8 or LTOS (henceforth "linguistic trend" T_{Lin}; see Materials and Methods for detailed description). Furthermore, if dorsomesial BA8 is specific to logic processes, we expect cTBS to this region to decrease accuracies for logic reasoning (but not for linguistic reasoning) more so than cTBS to either Broca's area or LTOS (henceforth "logic trend", T_{Log}). Indeed, for linguistic reasoning, T_{Lin} was significant ($F_{1,14} = 7.70$, $p = 0.015$) whereas T_{Log} was not ($F_{1,14} = 3.96$, $p = 0.066$; in fact, the marginal significance is due to a reverse pattern, with performance on linguistic problems after cTBS to mesial BA8 increasing by 3.3%, see Fig 1d). Furthermore, for logic reasoning, T_{Log} was significant ($F_{1,14} = 6.626$, $p = 0.022$) whereas T_{Lin} was not ($F_{1,14} = 0.038$, $p = 0.849$). In addition, we also find that accuracy for the grammaticality judgments was affected by cTBS in a pattern similar to that observed for linguistic problems (and thus opposite to the pattern observed for logic problems; Fig.1d). Specifically, inhibition of Broca's area led to a decrease in accuracy, by 6.8%, compared to pre-cTBS baseline, whereas inhibition of mesial BA8 and LTOS both lead to increased accuracy (by 2.9% and 6.6%, respectively). The trend analysis for grammaticality judgments thus returned a similar pattern to that obtained for linguistic problems (i.e., significant for T_{Lin} [$F_{1,14} = 11.221$, $p = 0.005$] and non-significant for T_{Log} [$F_{1,14} = 0.576$, $p = 0.460$]).

Discussion

A central paradigm shift in the cognitive approach to understanding the human mind has been the realization that while perceiving serially ordered sequences of (linguistic) utterances, we spontaneously build hierarchical abstract representations of the way that discrete elements bind to one another, thereby conferring meaning to otherwise meaningless strings of sounds [34, 35]. Although this ability is most obviously displayed in natural language, it characterizes several other aspects of human thought, such as algebra, music, and action sequences, among others [2]. Many have thus wondered whether the mechanisms for parsing the structured sequences of language also serve an analogous role in other domains of human cognition [10–12]. Here, we address this question in the context of the structured sequences of deductive reasoning, and present evidence contrary to the hypothesis that, in the adult brain, the structure-dependent operations of logic are parasitic on the mechanisms of language. For, it is possible to selectively impair the latter without affecting the former, as shown by the two-way interaction between stimulation site and performance change after brain stimulation. This result is consistent with neuropsychological evidence demonstrating that patients with lesions spanning frontomedial cortices (including our cTBS site in dorsomesial frontal cortex, BA8) are impaired at deductive reasoning despite no observable structural damage in Broca's area and ceiling performance on standard neuropsychological tests of language [36].

Although we tested the language-centric hypothesis of deduction in the context of a specific mode of deductive reasoning (i.e., propositional logic), previous work suggests that this conclusion can reasonably be expected to extend to categorical syllogisms [27, 37, 38], relational problems [39], and pragmatic inferences in the context of naturalistic discourse [40, 41]. The findings from this study, however, are still compatible with the Vygotskyan idea that language may serve, throughout development, as a "cognitive scaffolding" [3] enabling the acquisition of structure-dependent operations such as those of logic, to then become independent, in adulthood. Yet, recent evidence suggests that preverbal infants can already demonstrate elementary logic reasoning [42]. Indeed, it is noteworthy that in our adult participants, logic reasoning appears unaffected by inhibitory stimulation to Broca's area despite decreased accuracy in both linguistic reasoning and simple grammaticality judgments, further supporting the idea that there is a fundamental difference between the representations and operations of logic and those of natural language.

These results provide clear empirical evidence against the idea that the mechanisms of natural language participate in logic reasoning[1], beyond decoding verbally presented

[1] Of course we acknowledge that heuristics such as belief bias are exerted through language, but are not, themselves, logic processes.

information into mental representations [25, 26]. An additional level of inquiry afforded by this study is the investigation of brain-behavior relationships. It is one thing to demonstrate that two functions/processes (like language and thought in our study) can be dissociable at brain level, and yet another to associate convincingly the two functions/processes with specific neural systems. While the historically established association between language and Broca's area is reinforced by these results, the findings only offer weak support for the hypothesis that mesial prefrontal cortex includes the "core" substrate of deductive reasoning. This should have been perhaps expected, given the general understanding that deduction might well rely on the "concerted operation of several, functionally distinct, brain areas" [43], thus making it a harder process to disrupt with single-location stimulation. Consistent with this understanding, we have previously voiced the view that "core" deductive processes might be implemented in multiple brain areas, including both the mesial BA8 target as well as left rostrolateral prefrontal cortex, in BA10 [28, 33].

The lack of a cTBS effect on three versus four variable items is relevant to two ongoing debates. With respect to logic reasoning, the fact that cTBS to dorsomesial BA8 impaired equally three- and four-variable logic problems (t_{14} = -1.18, p = 0.13) is contrary to the idea that activity in this region can be explained by non-deductive processes, such as working memory demands imposed by complex deductions, [44] or greater relational complexity [45], confirming recent neuroimaging data [28]. With respect to linguistic reasoning, these results bear on the question of the role of Broca's area in language processing [7, 9, 46] and suggest that this region is key to processing the hierarchical, non-local, dependencies of natural language [7–9] and not just a reflection of verbal working memory [46]. For, not only does cTBS to this region impair the manipulation of long-distance relationships across non-canonical sentences, but it also fails to differentially affect three- versus four-variable problems (t_{14} = -0.197; p = 0.43), contrary to what a verbal working memory account would predict.

Conclusion

In conclusion, this work presents direct causal evidence from the adult healthy brain demonstrating that abstract logic reasoning can be dissociated with non invasive brain stimulation from the mechanisms of natural language, contrary to the hypothesis that language forms the basis of complex human thought [3–5].

Materials and methods

Participants

Fifteen participants took part in this study (twelve women, three men). The mean age was 21.1 and the age range was 18-30. Participants were recruited through flyers and from other (unrelated) studies. To be included, participants had to be right handed, native English speakers, between the ages of 18 and 50 years old, and have had no significant prior formal instruction in deductive reasoning. In addition, we only selected participants who had a recent structural MRI available (from previous participation in a neuroimaging experiment at UCLA) to allow for MR-guided targeting with the transcranial magnetic stimulation (TMS) coil on the basis of individual brain anatomy (see below). In keeping with TMS safety standards [47], participants were excluded if they had metal implants in their head, if they engaged in regular alcohol use, were pregnant, had a family history of seizures, had been diagnosed with any significant medical, psychiatric or neurological conditions, or used any prescription medication that could lower their seizure threshold (i.e. bupropion). Participants were compensated $25 per hour for their time. Total compensation for each completing participant ranged from $125 to $175.

Each participant attended four study visits. The first was a screening visit, which took place in the UCLA Psychology Department, at which the participant was consented and, after viewing one example trial for each task, performed a set of problems analogous to those employed in the subsequent cTBS sessions (except for superficial differences in the stimuli). Participants never received any feedback on either individual problems or overall performance. To be included in the TMS sessions of the study participants had to perform at or above 50% accuracy on the overall task and each of the three primary subcomponents (i.e. linguistic problems, logic problems, and grammaticality judgments, described below). Seven participants were excluded for being unable to meet this criterion (five men and two women) while fifteen went on to complete the study. The three TMS sessions took place at the UCLA Ahmanson-Lovelace Brain Mapping Center. Visits took place at least one week apart. In each TMS session, one of three sites was targeted in the left cerebral hemisphere; namely, Broca's area, in the pars opercularis of the inferior frontal gyrus (Brodmann area [BA] 44), dorsomesial frontal cortex (BA8), or transverse occipital sulcus (LTOS) (see below for procedure and coordinates). The order in which target sites were stimulated was counterbalanced across participants. At each visit, participants first performed a ten minute baseline cognitive task. They then underwent the TMS procedure, which included a stimulation thresholding procedure followed by the administration of cTBS. Approximately 2 to 3 minutes after the TMS procedure ended participants started performing a 30 minute post-cTBS task. All participants who began the experimental phase of the experiment completed the study. All procedures were approved by the UCLA Institutional Review Board.

Task and Stimuli

Task and stimuli materials were adapted from previous work [25]. For each of the three TMS sessions, participants were presented with 156 stimuli, in visual format. Each stimulus consisted of an argument, defined as a set of two sentences presented one above a horizontal line and one below (each sentence was presented on a single line). Half the arguments were "linguistic" in that they described a subject-object-patient relationship (i.e., "who did what to whom"; e.g., "Y gave X to Z." and "X was given Z by Y."). The remaining were "logic" in that they described the logic implicature tying phrasal constituents together (i.e., "X,Y, Z"; e.g. "If Y or X then not Z." and "If Z then not Y and not X.").

For each argument, participants were asked to perform one of two tasks. In the reasoning task, they were asked to establish whether the two sentences of each argument matched in that they described the same state of affairs (that is, they had to decide whether the two sentences were transformations of one another). Half the arguments presented in the reasoning trials described the same state of affairs and half did not. In the grammaticality judgment task, participants were asked to evaluate whether both sentences of each argument were grammatical (with no need to relate the two sentences to each other). Half the arguments presented in the grammaticality trials were grammatical and half were not. As done in previous work, ungrammatical arguments were obtained by altering word order in either sentence [25, 33]. Half the ungrammatical sentences had an error in the sentence above the line, and half had the error in the sentence below the line. Overall, the 156 arguments that participants saw at each session included 104 reasoning trials (half with "linguistic" arguments and half with "logic arguments") and 52 grammaticality judgment trials (also evenly divided between types of arguments).

It should be noted that, in the context of the reasoning task, linguistic and logic arguments emphasize different types of structure-dependent relationships. When presented with linguistic arguments, the reasoning task required understanding the thematic relations of "X,Y, Z" with respect to the major verb of the sentence, across different syntactic constructs (e.g. X is a patient in "It was X that Y saw Z take." but is an agent in "Z was seen by X taking Y."). When presented with logic arguments, the reasoning task required understanding the logic relations tying phrasal constituents together across different statements (e.g. "If both X and Z then not Y." and "If Y then either not X or not Z.").

In order to manipulate the relational complexity [45] of the arguments, for each type of problem, half the arguments contained three variables and half contained four variables. We also note that, for each task type, half the trials included statements concerning the relationships between three variables (e.g., "X was given Y by Z." and "If either X or Y then not Z.") and the remainder included statements concerning the relationship between 4 variables (e.g., "W heard that Z was seen by Y taking X." and "If either Z or W then both X and not Y."). For each type of problem, half the arguments featured sentences describing the same state of affairs (i.e., where the two sentences match in the circumstance they describe). Assignment of the variables W, X, Y, Z to elements/phrasal constituents was randomized across arguments.

In each session, the 156 arguments included 78 linguistic arguments and 78 logic arguments. For each type, 52 arguments were presented in reasoning trials, and 26 were presented in grammaticality judgment trials. Of the 156 trials, 36 (equally distributed across tasks) were presented prior to cTBS stimulation (i.e., baseline trials) and 120 (equally distributed across tasks) were presented after cTBS stimulation. The same 156 arguments were presented across the four sessions except for randomly allocating each argument to baseline or post-cTBS presentation and for different allocation of variables (i.e., W, X, Y, Z) to thematic roles/phrasal constituents. Within baseline and post-cTBS sequences, presentation order of each argument (and task) was randomized with the sole constraint that trials with identical parameters not occur consecutively.

Experimental Design

As shown in Fig. 1a, each trial began with a 1 second fixation cross followed by a 1 second cue signaling to the participant whether they were to perform a reasoning task (with either linguistic or logic materials), cued by the word "MEANING", or the grammaticality judgment task (with either linguistic or logic materials), cued by the word "GRAMMAR". The cue was followed by on-screen presentation of the argument, with the two sentences arranged vertically, one above the other, separated by a horizontal line (cf., Fig. **??**a). Given the randomized task order, a small "M" or "G" block letter at the top left of the screen served as a reminder of which tasks participants were expected to perform at each trial (as we have done in previous work [28]). Participants had up to a maximum of 15 seconds to press the A key for a positive answer (i.e., "the sentences describe the same state of affairs" and "both sentences are grammatical", for the reasoning and grammaticality judgment task, respectively) and the L key for a negative answer (i.e., "the sentences do not describe the same state of affairs" and "one of the two sentences is grammatically incorrect", for the reasoning and grammaticality judgment task, respectively). The trial terminated upon button-press or upon the elapsing of the allotted 15 s, after which a new trial would begin. Stimuli were delivered using Psychopy [48] on a Toshiba Satellite laptop running Windows 7.

Transcranial Magnetic Stimulation

For each participant, the FMIRB Software Library (FSL) [49] was used to transform the individual T1-weighted structural MRI – which had been obtained, with consent, from previous studies they had taken part in – into standard space (MNI template space). Stimulation targets were defined on the basis of previous published work. These included a target in Broca's area (x = -50, y = 18, z = 18)(Monti et al., 2009), centered on the pars opercularis of the left inferior frontal gyrus, one in dorsomesial frontal cortex (BA8) (x = -6, y = 40, z = 38) [25, 28], and a control site in the LTOS (x = -25, y = -85, z = 25) [32]. Two additional targets were used for the active motor thresholding (AMT) procedure. Coordinates for cortical stimulation of these two sites, the cortical representations of the first dorsal interosseous (FDI) muscle in the right hand, and the tibialis anterior (TA) muscle of the right leg, were also marked in standard space based on prior literature [50–52]. The targets, originally defined in MNI template space, were then projected back into the participant's native structural MRI space, to allow optimal TMS coil positioning for each target through the frameless stereotaxy Brainsight system (Rogue Research).

For TMS stimulation of the motor cortex representation of the right FDI muscle, Broca's area, and LTOS, a Magstim flat figure-eight (double 70 mm) coil was used. Because our mesial BA8 target and the motor cortex representation of the right TA muscle are located within the interhemispheric fissure, we used an angled figure-eight (double 110 mm) coil that allows better stimulation of deeper cortical areas. This method is similar to that used in previous studies [31, 53].

After participants completed the baseline task, the AMT was measured for that session's target site using a two-step procedure [31, 54]. For Broca's area and LTOS target sessions, "hot spot" coordinates were based on left motor cortex representation of the right FDI (flat figure-eight coil); for dorsomesial frontal cortex (BA8) target sessions, "hot spot" coordinates were based on left motor cortex representation of the right TA (angled figure-eight coil). Single TMS pulses were delivered while the target muscle was mildly activated. If single pulses from the coil did not produce motor evoked potentials (MEPs) of ≥200 μV at initial location, then the coil location was varied systematically around the initial target site until reliable MEPs were evoked at a suprathreshold intensity. Once the motor cortex "hot spot" was determined, the AMT was determined as the minimum TMS intensity at which motor evoked potentials (MEPs) of ≥200 μV were obtained in at least five out of ten consecutive stimulations under active target muscle conditions.

Following the thresholding procedure, cTBS was applied to the target. In cTBS, triplets of TMS pulses at 50 Hz are delivered at 5 Hz, giving a total of 600 pulses over a period of 40 seconds. The intensity was set at 80% of the AMT, in accordance with prior studies [31, 55]. For 12 out of 44 sessions (5 at which Broca's area was targeted, 1 at which mesial BA8 was targeted, and 6 at which TOS was targeted) the participant's AMT was too high for our TMS device to deliver cTBS without significant heating. For these sessions, instead of using 80% of AMT, we applied cTBS at the highest level allowed by the safety measures of our TMS device (43% of maximum stimulator output (MSO)). The cTBS pulse pattern was generated using a second generation Magstim Rapid2, and the average percentage of MSO used was 35.61% (with a range of 19%-43%).

Upon completion of the cTBS stimulation procedure, participants began the post-treatment task after a delay of approximately 2-3 minutes. The post cTBS portion of the experiment lasted for 30 minutes (the inhibitory effects of cTBS have previously been shown to last for 30 to 60 minutes) [30, 56]. Upon completion of all trials, participants filled out a brief questionnaire to assess how much pain and/or discomfort they experienced during the cTBS stimulation. Both the pain and discomfort scales asked the participant to rate, from 0 to 10, how much pain or discomfort they were in during the procedure, with 0 indicating no pain/discomfort and 10 indicating the worst pain/discomfort they had ever felt. Across all participants, the mean pain rating was

2.52 ($SD = 1.76$), while the mean discomfort rating was 3.25 ($SD = 1.88$). For each stimulation site, the mean pain ratings were as follows: 2.64 ($SD = 1.67$) for BA44, 3.33 ($SD = 2.09$) for BA8, and 1.60 ($SD = 0.80$) for TOS. For discomfort ratings at each stimulation site, the means were: 3.64 ($SD = 2.12$) for BA44, 3.87 ($SD = 1.71$) for BA8, and 2.27 ($SD = 1.34$) for TOS. It is worth noting that no participants who began the TMS component of the study failed to complete it.

Analysis

First, in order to remove accidental key presses from the results, all trials from all participants were ordered from fastest response time to slowest response time. Then, trials were binned into groups of ten, with accuracy and response time averaged within each bin to see if there was any response time threshold below which accuracy fell below 50%. There was no such threshold, but four individual trials had response times of less than one second which were deemed likely to have been accidental button presses and were thus removed from further consideration. Average accuracies for each combination of task and site for each participant were entered in the two following analyses.

Key analysis The specific predictions of the language-centric and language-independent views of deductive reasoning described in the main text were tested in a 2 × 2 ANOVA with two within-participants factors, site (Broca's area vs dorsomesial frontal cortex, BA8) and task (linguistic reasoning vs logic reasoning). The analysis was followed-up with planned directional testing of the simple effect of site on each task individually with pairwise t-tests.

Full analysis To report on the full set of sites and conditions tested, a 3 × 3 ANOVA with two within-participants factors, site (Broca's area vs dorsomesial BA8 vs LTOS) and task (linguistic reasoning vs logic reasoning vs grammaticality judgments), was also performed. The analysis was followed up through testing of the simple effect of site on each task individually with a contrast analysis (cf., Table S2). Specifically, for each task, we created two contrasts conceived to identify the presence of systematic associations between post-cTBS accuracy percent change and site. Specifically, we identified two possible trends (of interest). The "linguistic trend" (T_{Lin}) contrast was specified in order to mark, where significant, tasks more sensitive to disruption of Broca's area than either dorsomesial BA8 or LTOS. T_{Lin} was thus obtained by setting contrast weights to -1 for Broca's area and 0.5 for mesial BA8 and LTOS. The "logic trend" (T_{Log}) contrast was specified in order to mark, where significant, tasks more sensitive to disruption of dorsomesial BA8 than Broca's area and LTOS. T_{Log} was thus obtained by setting contrast weights to -1 for dorsomesial BA8 and 0.5 for Broca's area and LTOS.

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Author Information

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Supporting information

Table S1. Example stimuli. Sample logic and linguistic arguments presented in the reasoning and grammaticality judgment tasks. (Abbreviations: Log, Logic; Ling, Linguistic.)

		Reasoning task	
Type	**Terms**	**Matching**	**Non-matching**
Log	**3**	If both X and Z then not Y. If Y then either not X or not Z.	If either Y or Z then not X. If X then both Y and Z.
Log	**4**	If both X and not Z then either Y or not W. If both W and not Y then either Z or not X.	If both not Y and not W then both Z and X. If both Z and X then both not Y and not W.
Ling	**3**	It was X that Y saw Z take. Z was seen by Y taking X.	It was Y that Z thought X said. Z was thought by Y to have said X.
Ling	**4**	It was X that W heard Y saw Z take. W heard that Z was seen by Y taking X.	What W knew that Y gave Z was X. It was X that W knew was given to Y by Z.

		Grammaticality judgment task	
Type	**Terms**	**Grammatical**	**Non Grammatical**
Log	**3**	If either Y or X then not Z. If Y then either X or Z.	If not Y then Z both and X. If either not Z or not X then not Y.
Log	**4**	If either X or W then both Y and Z. If both not Y and not W then both Z and X.	If both Z and not Y then either X or not W. If both W and Y then either not X not or Z.
Ling	**3**	Z was thought by Y to have said X. It was Y that X thought Z said.	It was to Y that from Z told X. What Z told Y was X.
Ling	**4**	Z knows that X is given by Y to W. If either W or X then both Y and not Z.	Z will be seen by Y taking X is what W will hear. It was X that W heard Y take Z saw.

Table S2. Linear trend analysis. For each task, contrast weights per stimulation site are given, followed by F value and significance. Significant trends highlighted in bold. (° As mentioned in the main text, marginal significance is due to a "reverse" effect where linguistic reasoning appear to ameliorate after mesial BA8 cTBS. Abbreviations: Ling, Linguistic; Log, Logic; Gramm, Grammaticality Judgment.)

	Linear trend weights	F	p
Ling	**T_{Lin} Broca (-1) vs [LTOS (+.5) & mesial BA8 (+.5)]**	**7.697**	**0.015**
	T_{Log} [Broca (+.5) & LTOS (+.5)] vs mesial BA8 (-1)	3.966	0.066°
Log	T_{Lin} Broca (-1) vs [LTOS (+.5) & mesial BA8 (+.5)]	0.038	0.849
	T_{Log} Broca (+.5) & LTOS (+.5) vs mesial BA8 (-1)	**6.626**	**0.022**
Gramm	**T_{Lin} Broca (-1) vs LTOS (+.5) & mesial BA8 (+.5)**	**11.22**	**0.005**
	T_{Log} Broca (+.5) & LTOS (+.5) vs mesial BA8 (-1)	0.576	0.46