Dissociating language and thought in human reasoning

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Introduction

Does language shape human cognition?[2,23] One aspect of this debate concerns whether the combinatorial operations of natural language also serve, supramodally[9,10,44], as a basis for the combinatorial operations of other domains of human thought such as mathematics[1,27,48], music cognition[21,30,5], and theory of mind[46,47], among others. In the context of human reasoning, a growing body of research has generated two opposing views concerning the role of language in enabling deductive inference-making[24]. Under the first, the structure-dependent operations required for deductive reasoning are linguistic in nature and thus based on the neural mechanisms of natural language[36,35]. Under the second, deductive reasoning is supported by language-independent processes principally implemented in frontomedial and left frontopolar cortices (in Brodmann areas [BA] 8 and 10, respectively)[25,26,38,7]. We tested the two competing views using continuous Theta Burst Stimulation (cTBS)[15], an inhibitory neuromodulation approach. Here, we report a neural dissociation between the structure-dependent operations of natural language and those of deductive reasoning. Specifically, we found that transient cTBS inhibition of Brocas area, in the left inferior frontal gyrus (IFG), a region often associated with processing the hierarchical dependencies of natural language[12,13], impairs accuracy for linguistic problems but not for logic ones. Conversely, cTBS to frontomedial cortices produces the opposite pattern. Our results demonstrate that, in the adult brain, the structure-dependent operations of reasoning are not parasitic to the neural substrate of natural language.

Continuous Theta Burst Stimulation (cTBS) has been shown capable of transiently inhibiting neural tissue, thereby modulating cognition and behavior[6,15]. Here, we employ this technique to distinguish between the two opposing views of human reasoning. Specifically, if the mental operations of deductive reasoning depend on the mechanisms of natural language, as posited by the language-centric view of deduction[36,35], transient cTBS inhibition of the region traditionally referred to as Brocas area, in the left inferior frontal gyrus, ought to decrease performance (i.e., accuracy) for both linguistic and deductive reasoning to a comparable extent. Conversely, if the two mental domains do not share a common substrate in the structure-dependent mechanisms of natural language, as posited by the language-independent view of deduction[25,26,38,7], cTBS to Brocas area ought to impair linguistic reasoning while sparing logic reasoning. Furthermore, the language-independent view also predicts that cTBS to frontomedial cortex, in mesial BA8, a

region previously described as core for deductive inference[26,38], should impair logic reasoning while sparing linguistic reasoning.

As shown in Fig 1a,b, we tested the above predictions with an experimental design including two sites of interest (Brocas area, mesial BA8), as well as a hypothesis neutral site (left transversal occipital sulcus; LTOS), and two tasks of interest (linguistic reasoning, logic reasoning), as well as a third control task (all adapted from previous work; see Methods section[26]). 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.) (see Table 1 for examples of stimuli). However, since we found no significant main effect of 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 omitted this variable from the report below. Overall, collapsing across stimulation sites and across pre- and post-cTBS trials, we find accuracy for linguistic reasoning and grammaticality judgments to be higher than for logic reasoning (83%, 84%, and 73%, respectively; see Table 3).

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 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[41], 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). 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; namely, Brocas area, in the pars opercularis of the left inferior frontal gyrus (Brodmann area [BA] 44), mesial BA8, or left 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 thresholding procedure followed by the administration of cTBS. Approximately 2 to 3 minutes after the TMS procedure ended they performed a 30 minute post-cTBS task. All participants who began the experimental phase of the experiment completed the experiment. All procedures were approved by the UCLA Institutional Review Board.

Task and Stimuli

Task and stimuli materials were adapted from previous work[26]. 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 (one presented above a horizontal line and one below). 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 affair 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.[26,27] 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[14] 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.

Table 1: **Example stimuli.** Sample logic and linguistic arguments presented in the reasoning and grammaticality judgment tasks.

		Reasoning task	
Arg. type	**Terms**	**Matching**	**Non-matching**
Logic	**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.
Logic	**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.
Linguistic	**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.
Linguistic	**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	
Arg. type	**Terms**	**Correct**	**Incorrect**
Logic	**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.
Logic	**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.
Linguistic	**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.
Linguistic	**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.

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. 1a). 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[7]). 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[31] on a Toshiba Satellite laptop running Windows 7.

Transcranial Magnetic Stimulation

For each participant, the FMIRB Software Library (FSL)[43] 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 Brocas area (x = -50, y = 18, z = 18)(Monti et al., 2009), centered on the pars opercularis of the left inferior frontal gyrus, one in mesial BA8 (x = -6, y = 40, z = 38)[7,26], and a "hypothesis neutral" target in the LTOS (x = -25, y = -85, z = 25)[16]. Two additional targets were used for the active motor thresholding (AMT) procedure. Coordinates for cortical stimulation of these two sites, 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[22,28,42]. The targets, originally defined in MNI template space, were then projected back into the participants 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, Brocas 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 (110 mm double cone) coil to deliver pulses to these areas. This method is similar to that used in previous studies[6,17]. After participants completed the baseline task, the AMT was measured for that sessions target site using a two-step procedure[6,8]. For Brocas area and LTOS target sessions, "hot spot" coordinates were based on left motor cortex representation of the right FDI (flat figure-8 coil); for mesial BA8 target sessions, "hot spot" coordinates were based on left motor cortex representation of the right TA (double cone 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 $\geq$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 $\geq$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[6,11]. For 12 out of 44 sessions (5 at which Brocas area was targeted, 1 at which mesial BA8 was targeted, and 6 at which TOS was targeted) the participants 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)[15,29]. 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 (Brocas area vs mesial 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.

Table 2: 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.)

	Linear trend weights	F	p
Linguistic	**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°
Logic	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**
Grammar	**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

Full analysis. To report on the full set of sites and conditions tested, a 3 × 3 ANOVA with two within-participants factors, site (Brocas area vs mesial 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. 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 Brocas area than either mesial BA8 or LTOS. T_{Lin} was thus obtained by setting contrast weights to -1 for Brocas 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 mesial BA8 than Brocas area and LTOS. T_{Log} was thus obtained by setting contrast weights to -1 for mesial BA8 and 0.5 for Brocas area and LTOS.

Results

In what follows, we first present the key analysis directly assessing the specific ex ante hypotheses outlined above (in a 2×2 within-subjects ANOVA framework) and we then expand the analysis to the hypothesis neutral site and control task (in a 3×3 framework; henceforth, full analysis).

Table 3: 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 reasoning	91%	83%	78%	81%	80%	80%
Logic reasoning	70%	75%	75%	73%	67%	76%
Grammaticality judgment	89%	82%	82%	84%	77%	84%

A 2×2 within-subjects ANOVA over participants post-cTBS accuracy percent change relative to pre-cTBS baseline accuracy revealed a significant cross-over interaction ($F_{1,14} = 9.67$, $p = 0.008$, $\eta_p^2 = 0.41$) between stimulation site (Brocas area versus mesial 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. Planned directional testing of the ex-ante hypotheses described above revealed that transient cTBS inhibition of Brocas 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 Brocas 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 pattern is contrary to the prediction of the language-centric view and consistent with the prediction of the language-independent view. Conversely, transient inhibition of mesial BA8 resulted in the opposite pattern (Fig. 1b), with post-cTBS accuracy for logic reasoning decreasing by 1.5% and post-cTBS accuracy for linguistic reasoning increasing by 3.3%, compared to pre-cTBS baseline. Nonetheless, while this pattern is in line with the language-independent view, the difference was not statistically significant ($t_{14} = -0.99$, $p = 0.17$; see discussion below).

Inclusion of the third, hypothesis neutral, site as well as the grammaticality judgment task[26,27] 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 in the key analysis and uncovered 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

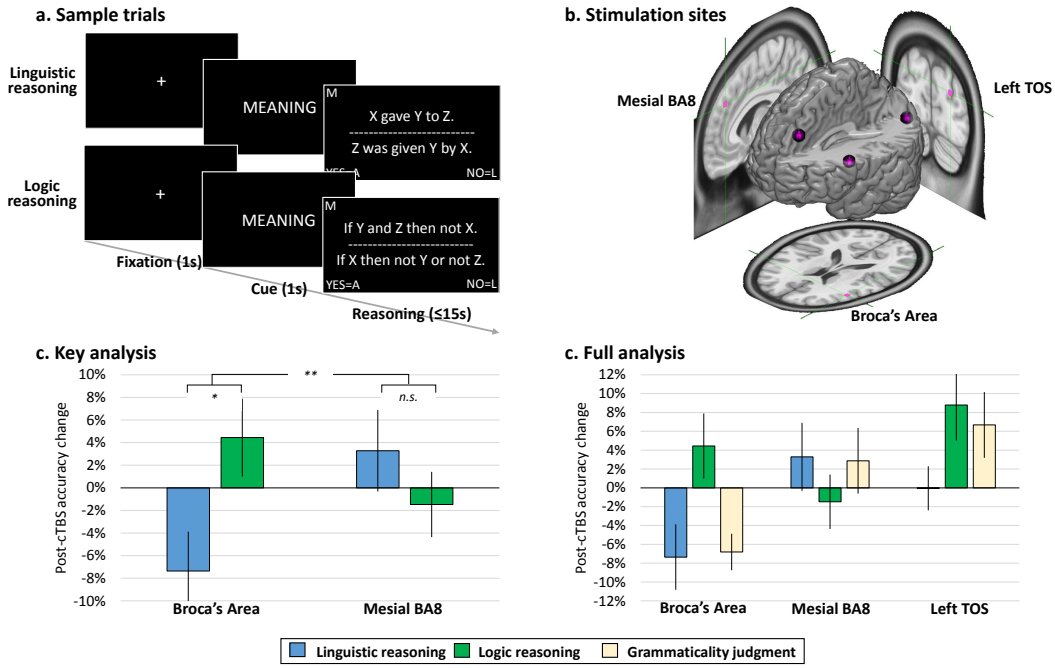

Figure 1: **Experimental design and results:** (a) Timeline and sample trials for a linguistic reasoning and a logic reasoning trial (see Table 1 for sample grammaticality judgment stimuli). (b) cTBS target sites: Brocas area (aimed at the pars opercularis of the inferior frontal gyrus; MNI coordinates: x = -50, y = 18, z = 18 [26], mesial BA8 (MNI coord: x = -6, y = 40, z = 38 [26,7], and LTOS (MNI coord: x = -25, y = -85, z = 25 [16]. (c) Key analysis result: Percent accuracy change for linguistic (blue) and logic (green) reasoning after cTBS to Brocas 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 Brocas 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.).

LTOS target (cf., Fig. 1d). Finally, in order to further test the relationship between site and task, we performed a trend analysis. If indeed Brocas area is specific to linguistic processes, we expect cTBS to this region to decrease accuracies for linguistic reasoning (but not for logic reasoning) more so than cTBS to either mesial BA8 or LTOS (henceforth linguistic trend T_{Lin}; see Methods for detailed description and contrast weight settings). Conversely, if indeed mesial 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 Brocas area or LTOS (henceforth logic trend, T_{Log}). Consistent with the result described above, 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). Conversely, 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 were 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 Brocas area leads 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 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

Overall, these data do not support 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, by transient inhibition of Brocas area, without affecting the former. This result is consistent with neuropsychological evidence demonstrating that patients with lesions spanning frontomedial cortices (including our cTBS site in mesial BA8) are impaired at deductive reasoning despite no observable structural damage in Brocas area and ceiling performance on standard neuropsychological tests of language[37]. 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 might well extend to categorical syllogisms[32,38,45] and relational problems[18]. The present data 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[4]. Indeed, it is noteworthy that in our adult participants, logic reasoning appears unaffected by inhibitory stimulation to Brocas 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. While these results provide clear empirical evidence against the idea that the mechanisms of natural language participate in logic reasoning* (beyond decoding verbally presented information into mental representations[25,26], they only offer weak support for the hypothesis that medial prefrontal cortex includes the core substrate of deductive reasoning. For, while we numerically observe the pattern predicted by previous neuroimaging results[25,26,7] and the aforementioned neuropsychological data[37], it was not statistically meaningful. It remains to be understood whether this is a consequence of methodological limitations of the approach (e.g., the degree to which deep medial regions can be efficiently stimulated via transcranial magnetic stimulation) or whether it should have been expected given the general understanding that deduction might well rely on the concerted operation of several, functionally distinct, brain areas[34], 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[27]. Finally, the failure of cTBS to differentially affect problems with three versus four variables is relevant to two ongoing debates. With respect to logic reasoning, the fact that cTBS to mesial BA8 impaired equally three- and four-variable logic problems (t_{14} = -1.18, p = 0.13) is contrary to the idea that this region can be explained by non-deductive processes such as working memory demands imposed by complex deductions[19] or greater relational complexity[14], confirming recent neuroimaging data[7]. With respect to linguistic reasoning, these results bear on the question of the role of Brocas area in

*Of course we acknowledge that effects such as belief bias are exerted through language, but are not, themselves, logic processes.

language processing[12,13,39] and suggest that this region (and the pars opercularis target in particular) is key to processing the hierarchical, non-local, dependencies of natural language[12,13] and not just a reflection of verbal working memory[39]. For, not only does cTBS to this region impair manipulating long-distance relationship 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. In conclusion, this work presents direct, causal, evidence from the adult healthy brain demonstrating that abstract logic reasoning is ontologically distinct[20,33] from the mechanisms of natural language, contrary to the popular idea that Brocas area serves as a supra-modal hierarchical parser across domains of human thought[44,40,9].

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Author statement

JPC, MAJ, MI, and MM designed the study. JPC and MAJ collected the data under ADWs supervision. JPC, MI, and MI conducted the analysis. JPC and MM drafted the paper. All authors contributed to critical revision of the initial draft.

Author Information

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