



**HAL**  
open science

## Contradiction in Universal and Particular Reasoning

Maria Teresa Medaglia, Franca Tecchio, Stefano Seri, Giorgio Di Lorenzo,  
Paolo Maria Rossini, Camillo Porcaro

► **To cite this version:**

Maria Teresa Medaglia, Franca Tecchio, Stefano Seri, Giorgio Di Lorenzo, Paolo Maria Rossini, et al.. Contradiction in Universal and Particular Reasoning. *Human Brain Mapping*, 2009, 30 (12), pp.4187-n/a. 10.1002/hbm.20838 . hal-00494650

**HAL Id: hal-00494650**

**<https://hal.science/hal-00494650>**

Submitted on 24 Jun 2010

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



## Contradiction in Universal and Particular Reasoning

|                               |  |
|-------------------------------|--|
| Journal:                      | <i>Human Brain Mapping</i>   |
| Manuscript ID:                | HBM-08-0490.R2   |
| Wiley - Manuscript type:      | Research Article   |
| Date Submitted by the Author: | 19-May-2009  |
| Complete List of Authors:     | <p>Medaglia, Maria Teresa; University "Roma Tre", Philosophy Department<br/>           Tecchio, Franca; CNR, ISTC; Casa di Cura SAN RAFFAELE Cassino e IRCCS SAN RAFFAELE PISANA<br/>           Seri, Stefano; Aston University, The Wellcome Trust Laboratory for MEG Studies, School of Life and Health Sciences<br/>           Di Lorenzo, Giorgio; University of Rome "Tor Vergata", Laboratory of Psychophysiology, Psychiatric Clinic, Department of Neuroscience<br/>           Rossini, Paolo; Campus Bio-Medico University, Clinical Neurology; Casa di Cura SAN RAFFAELE Cassino e IRCCS SAN RAFFAELE PISANA<br/>           Porcaro, Camillo; Birmingham University, School of Psychology and Birmingham University Imaging Centre (BUIC); AFaR, Fatebenefratelli Hospital, Isola Tiberina; ITAB, Institute for Advanced Biomedical Technologies</p> |
| Keywords:                     | Contradictory Reasoning, Electroencephalography (EEG), Independent Component Analysis (ICA), Logical operators   |
|                               |  |



1  
2  
3 Reviewer: 1  
4 Comments to the Author  
5

6 This is my second review of "Contradiction in Universal and Particular  
7 Reasoning" by Medaglia et al.. I think that the authors have  
8 thoughtfully taken into account my comments and I recommend the  
9 manuscript for publication. Nevertheless, I have a series of, mostly,  
10 rhetorical comments.  
11

12 Going in order of page numbers:  
13

14 Abstract: The second sentence should indicate which technique the  
15 authors used to find their results.

16 ➤ The sentence was introduced in the new version of the manuscript.  
17

18 Abstract: The description of the results in the abstract should be  
19 written in the past tense (e.g., "The cerebral network involved in the  
20 identification of contradiction included", "The event-related dynamic  
21 of this network showed", "this was followed" etc...)  
22

23 ➤ Following the suggestion of the reviewer, we rewrote the abstract  
24 using the past tense.

25 Page 3, line 1: Reasoning is one of the core expressions of human  
26 intelligence and is pivotal to effective social interactions, as well  
27 as for the solution of everyday practical problems -> Reasoning is  
28 one of the core expressions of human intelligence and is pivotal to  
29 effective social interactions, as well as to the solution of everyday  
30 practical problems.

31 ➤ The sentence was changed in the new version of the manuscript.  
32

33 General comment for Results: The term "effect" should be used instead  
34 of "factor" in sentences like "absence of any main factor" (p8), "main  
35 Logical Operator factor", or "clear interaction factors" (p9)

36 ➤ Following the suggestion of the reviewer, we changed the word  
37 "factor" with "effect" in the Results section.  
38

39 Page 8, line 39: The new sentence "All data on RN activity refer to  
40 trials with correct identification" should be moved to the Methods  
41 (Data Analysis) section.

42 ➤ The sentence was moved in the end of the Data Analysis section.  
43

44 Page 8, line 53: Broadman -> Brodmann

45 ➤ The typo error was changed in the new version of the manuscript.  
46

47 Page 8, line 53: The RN included the Temporo-polar cortex bilaterally  
48 - middle temporal gyrus Broadman Area (BA) 21 and the most rostral part  
49 of the superior and middle temporal gyri BA 38 -, the Orbitofrontal  
50 cortex - BA 10, 11 and 47 - bilaterally the Anterior Cingulate - BA 32  
51 - bilaterally consistently across subjects (Fig. 3, Table 3). ->  
52 Consistently across subjects, the RN included the bilateral Temporo-  
53 polar cortex (middle temporal gyrus, Brodmann Area (BA) 21, and the  
54 most rostral part of the superior and middle temporal gyri, BA 38), the  
55 bilateral Orbitofrontal cortex (BA 10, 11 and 47) and the bilateral  
56 Anterior Cingulate cortex (BA 32) (Fig. 3, Table 3).

57 ➤ We rewrote the sentence as indicated by the reviewer.  
58  
59  
60

1  
2  
3 Page 9, line 19: this section begins with "As for the involved  
4 anatomical structure" but there is not mention of any anatomical  
5 structures in the paragraph.

6 ➤ The sentence was modified in the new version of the manuscript.  
7

8 Page 11, line 19: Our results could be interpreted to mean that -> Our  
9 results suggest that

10 ➤ The sentence was modified in the new version of the manuscript.  
11

12 Page 12, line 10: these cortical regions are necessary to predict ->  
13 activity in these region is predictive of

14 ➤ The sentence was modified in the new version of the manuscript.  
15

16 Page 12, line 14: the orbitofrontal cortex (OFC) appears to be involved  
17 in promoting risk taking -> enhanced activity in the orbitofrontal  
18 cortex (OFC) is associated with risk-taking behavior

19 ➤ The sentence was modified in the new version of the manuscript.  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

## Contradiction in Universal and Particular Reasoning

*Maria Teresa Medaglia<sup>1,4</sup>, Franca Tecchio<sup>2,8</sup>, Stefano Seri<sup>4</sup>, Giorgio Di Lorenzo<sup>6</sup>,  
Paolo M. Rossini<sup>7,8</sup>, Camillo Porcaro<sup>3,2,5</sup>*

<sup>1</sup>Facoltà di Lettere e Filosofia, University “Roma Tre”, Philosophy Department, Rome, Italy

<sup>2</sup>ISTC-CNR, Ospedale Fatebenefratelli, Isola Tiberina, 00186 Rome, Italy

<sup>3</sup>School of Psychology and Birmingham University Imaging Centre (BUIC), University of Birmingham, Birmingham, UK

<sup>4</sup>The Wellcome Trust Laboratory for MEG Studies, School of Life and Health Sciences, Aston University, Birmingham, UK

<sup>5</sup>ITAB –Institute for Advanced Biomedical Technologies, “G. D’Annunzio” University, Chieti, Italy

<sup>6</sup>Laboratory of Psychophysiology, Psychiatric Clinic, Department of Neuroscience, University of Rome “Tor Vergata”, Rome, Italy

<sup>7</sup>Clinical Neurology, Campus Bio-Medico University, Rome, Italy

<sup>8</sup>Casa di Cura SAN RAFFAELE Cassino e IRCCS SAN RAFFAELE PISANA, Italy

**Short Title:** Contradictory Reasoning

**Keywords:** Contradictory Reasoning, Electroencephalography (EEG), Independent Component Analysis (ICA), Logical operators.

**Corresponding author:**

Dr. Camillo Porcaro

Research Fellow

School of Psychology

University of Birmingham

Edgbaston

Birmingham B15 2TT

UK

Tel. 0121 414 5637

Email: c.porcaro@bham.ac.uk

**ABSTRACT**

A wide range of essential reasoning tasks rely on contradiction identification, a cornerstone of human rationality, communication and debate founded on the inversion of the logical operators 'Every' and 'Some'. A high-density electroencephalographic (EEG) study was performed in 11 normal young adult. The cerebral network involved in the identification of contradiction included the orbito-frontal and anterior-cingulate cortices and the temporo-polar cortices. The event-related dynamic of this network showed an early negative deflection lasting 500 ms after sentence presentation. This was followed by a positive deflection lasting 1.5 s, which was different for the two logical operators. A lesser degree of network activation (either in neuron number or their level of phase locking or both) occurred while processing statements with 'Some', suggesting that this was a relatively simpler scenario with one example to be figured out, instead of the many examples or the absence of a counterexample searched for while processing statements with 'Every'. A self-generated reward system seemed to resonate the recruited circuitry when the contradictory task is successfully completed.

## INTRODUCTION

Reasoning is one of the core expressions of human intelligence and is pivotal to effective social interactions, as well as to the solution of everyday practical problems. The identification of contradiction, which is crucial for logical reasoning, plays an important role in communication, understanding and learning. Western culture, which largely derives its models from Aristotelian logic, relies on a model that polarizes contradictory perspectives, i.e., deciding if two apparently divergent propositions are contradictory. In philosophical and historical perspective, contradictions are embedded in the social structure of society and can inherently lead to economic and cultural crises and eventually revolutions. In conversations, when trying to prove the contradiction of a general statement we frequently search for a counterexample. To refute the statement 'Every man is tall', it is therefore sufficient to state 'Napoleon is short'. In logic, the same statement would be contradicted with the formulation 'Some men are short'. Above and beyond being fundamental structures in logic, 'Every' and 'Some' are key conceptual categories of human reasoning. We rely on these operators when generalizing properties of objects or phenomena or alternatively to describe their specific attributes. 'Every' and 'Some', pervade natural language, provide a means of communicating quantities and are central to conducting a debate. A profound cultural awareness of the importance of these categories promotes communication and dialogue aptitude across the whole of society.

Considerable progress has been made over the past decade in understanding the neural basis of human reasoning (Goel 2007a; Kroger et al. 2008) with the aid of non-invasive brain imaging tools. Techniques like functional magnetic resonance (fMRI) (Goel et al. 2000, 2001, 2003a, 2003b, 2004, 2007b; Prado and Noveck 2007; Newstead et al. 1997) and electroencephalography (EEG) (Prado et al. 2008; Luo et al. 2008; Qiu et al. 2007) offer a window on brain function that is complementary to more traditional measurements of psychophysical performance, such as reaction times and other psychometric parameters. Extensive and distributed brain networks organized with a high degree of modularity have been so far identified as sustaining logical reasoning, with a consistent involvement of frontal areas (Goel 2007a; Greene et al. 2004).

In this study we have used high resolution EEG to investigate the electrophysiological correlates of cognitive processing while identifying whether a conclusion correctly contradicted a premise. Given the complexity of the putative processing networks, we decided to approach the reasoning network recognition through Independent Component Analysis (ICA). Surprisingly, to researchers accustomed to thinking that EEG sources can only be separated by solving the biophysical inverse problem, ICA does not require any "a priori" assumptions on network properties or head model during the separation step. This algorithm is able to identify the brain

1  
2  
3 sources supporting the investigated function by exploiting the most accurate information provided  
4 by the electrophysiological techniques, i.e. the dynamical properties of the recorded signal (Porcaro  
5 et al. 2009; Barbati et al. 2004; Makeig et al. 2002; Jung et al. 2000). Beyond separating  
6 stereotyped non-brain artifact signals including eye movements, line noise, cardiac artifacts and  
7 muscle activities (Makeig et al. 2004), ICA can identify large or small neuronal pool activities with  
8 diverse physiological and functional roles (Vorobyov and Cichocki 2002; Hyvärinen and Oja 2000;  
9 Makeig et al. 1999). Appropriate procedures must be applied to identify the ICs representing brain  
10 sources of interest, generally with a set of ICs corresponding to one brain source with specific  
11 spatio-temporal properties. After IC separation on the basis of time signal statistical properties, and  
12 after the second step of IC identification on the basis of the expected spatio-temporal  
13 characteristics, proper algorithms must be run to characterize the 3D configuration of these sources.  
14 In other words, after IC separation, ICA allows the use of source localization algorithms having  
15 isolated the field distribution generated by the specific source of interest.  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25

26 We used typical forms within the Aristotelian categorical proposition structure in the context  
27 of a naturalistic debate, presenting premise-conclusion pairs like ‘Every man is mortal – Some men  
28 are immortal’. The two sentences were presented in a dialogue-like fashion, with a proponent  
29 formulating a statement, and an opponent attempting its refutation. The subject was asked to  
30 recognize the correctness of the opponent refutation independent of the correctness of the sentence  
31 content (Fig. 1). We investigated whether identification of contradiction corresponded to different  
32 activation dynamics for the universal (‘Every’), as opposed to the particular (‘Some’) operator. To  
33 this end, the 200 premise-conclusion couples were evenly divided between contradictory (C) and  
34 not contradictory (NC), half of them presenting a premise with the ‘Every’ logical operator  
35 (UNIVERSAL) and the other half with the ‘Some’ logical operator (PARTICULAR).  
36  
37  
38  
39  
40  
41  
42  
43  
44

## 45 MATERIALS AND METHODS

### 46 *Subjects*

47  
48  
49 Subjects consisted of 11 healthy native Italian speakers (mean age: 30.5 years; range: 24 –  
50 38 years; 5 men, 6 women) took part in this experiment. None of the subjects had specific  
51 background knowledge or experience in logic. Subjects gave their informed written consent after  
52 the nature of the study was explained to them. The study occurred at Aston University and was  
53 authorized by the Aston University Ethics Committee. All subjects were healthy, right-handed and  
54 had normal or corrected-to-normal vision.  
55  
56  
57  
58  
59  
60

### *EEG recordings*

Scalp EEG signals were recorded continuously during the protocol using an EGI data acquisition system (Electrical Geodesics, Inc., Eugene, OR, USA; <http://www.egi.com>) with the third generation of EGI dense array net, the HydroCel Geodesic Sensor Net® (128-channel HCGSN – Tucker 1993). Gain and zero calibration were performed before the start of each EEG recording; channel impedances were kept below 50 kΩ for all net sensors (Ferree et al. 2001). EEG amplified signals were sampled at 500 Hz (pre-sampling analogical filter 0.1–200 Hz) and collected for off-line processing. All channels were referenced to the vertex (Cz) electrode.

### *Stimuli*

Subjects were comfortably seated at a distance of 1 meter from the front of a 19-inch monitor. Stimulus presentation was carried out via a Dell PC using E-Prime experimental programming software (Psychology Software Tools, Inc.; <http://www.pstnet.com>), which provides triggers for the EGI recording apparatus with highly accurate timing. The protocol contained 200 pairs of sentences, evenly divided into the following four forms: 50 Every Some – Contradictory (ES-C), 50 Some Every – Contradictory (SE-C) and 50 Every Some – Not Contradictory (ES-NC), 50 Some Every – Not Contradictory (SE-NC). In the ES-C and ES-NC the premise is universal (E: Every) and the conclusion is particular (S: Some), with the conclusion contradictory for the first set (ES-C) and not contradictory for the other (ES-NC). Similar conditions were used for the SE-C and SE-NC.

For example, one set of the four conditions is provided in Table 1. The four conditions were randomly presented.

### *Experimental Setup*

Prior to recording, the experiment was described to the subjects (Fig. 1) and they were given a test training session. Subjects were asked to evaluate whether the conclusion was contradictory or not, with respect to the premise independent of the correctness of the sentence content. After the conclusion was reached, and at the appearance of a go signal (a question mark), subjects had to press one push button if the conclusion contradicted the premise and a different push button if the conclusion did not. If they were unable to make a clear choice, they were told to omit the response (i.e., to not push either button).

### *Data Analysis*

The data were low pass filtered (100Hz) prior to the off-line analysis. The analysis strategy aimed at extracting signals generated only in response to the task. For this purpose, we assumed the set of EEG signals to be generated by the mixing model:

$$\mathbf{x}(t) = \mathbf{A}\mathbf{s}(t), \quad (1)$$

where  $t = 0, 1, 2, \dots$  is the discrete sampling time;  $\mathbf{x}(t) = [x_1(t), \dots, x_m(t)]$  is the  $m$ -dimensional vector of the observed signal recorded by  $m$  sensors;  $\mathbf{A}$  is an  $m \times n$  (with  $n \leq m$ ) unknown full-rank mixing matrix;  $\mathbf{s}(t) = [s_1(t), \dots, s_n(t)]^T$  is the  $n$ -dimensional unknown vector of the sources (Fig. 2). The model is approached by processing sensor signals by an ICA demixing system described in the form:

$$\mathbf{IC}(t) = \mathbf{W}\mathbf{x}(t), \quad (2)$$

where  $\mathbf{IC}(t) = [IC_1(t), \dots, IC_n(t)]^T$  is the  $n$ -dimensional vector of the estimated Independent Components (ICs) and  $\mathbf{W}$  is the separation matrix, i.e., the estimate of the inverse of the unknown mixing matrix  $\mathbf{A}$ , up to permutation and scaling:

$$\mathbf{W} = \hat{\mathbf{A}}^{-1}. \quad (3)$$

We used the FastICA algorithm proposed by Hyvärinen (Hyvärinen et al. 1999, 2001).

In the case of a high number of channels (128 in our case), a direct extraction of all the ICs would have been extremely time consuming and component selection extremely challenging. We pursued a dimensionality reduction by applying an optimized procedure to select a  $k$  ICs-subset such that the corresponding explained variance will be at least 95% (Salustri et al. 2005). This was proven to be a suitable procedure for subspace reduction and avoided the time consuming estimation of all ICs in the case of high space dimensionality corresponding to the high number of channels. In our case, on average, 39 ICs [range 27- 49] resulted in a mean explained variance  $\pm$  standard deviation of 97.58%  $\pm$  1.12%.

*Selection criteria of Reasoning Network (RN) ICs* As determined by the improvements of ICA model applications, introduced for example in the context of fMRI (Beckmann et al. 2004) and Foetal Magnetoencephalography (Porcaro et al. 2006), we selected among the above described IC subset (of about 39 ICs) of those components showing appropriate spatio-temporal characteristics. We required significant event-related responses triggered by the conclusion presentation. To this end, each IC dynamic was averaged, triggered on the second sentence presentation for the time window including the premise, and lasting until the start of the next trial. As we used a constant inter-stimulus interval between the premise and conclusion (3 s) in our paradigm, a single average

evidenced the phase locked response of the IC to both sentences. The single trial and time-frequency behaviors, as well as the topographical distribution, were used to identify ICs of interest (RN ICs, Fig. 2).

*Reasoning Network localization* After RN identification, its position was estimated in each subject by retro projecting only the RN ICs and obtaining the electric potential distribution:

$$\mathbf{EEGrec}_k = \mathbf{A}_k \mathbf{IC}_k, \quad (4)$$

where  $\mathbf{A}_k$  is the estimated mixing vector (matrix A of equation 1) for the source  $\mathbf{IC}_k$  and  $\mathbf{EEGrec}_k$  is the resulting  $\mathbf{IC}_k$  retro-projection on the channels space. We submitted  $\mathbf{EEGrec}_k$  to a source localization algorithm (sLORETA) (Pascual-Marqui 2002) as implemented on CURRY<sup>®</sup> software (<http://www.neuroscan.com>).

*Reasoning Network dynamics* The RN IC dynamics were studied in response to the presentation of the premise and the conclusion, i.e., analyzing the two time periods lasting [-0.5, 2.5] s, with 0 being the sentence presentation. The RN dynamics were studied in the four different experimental conditions ES-C, ES-NC, SE-C and SE-NC, referring to trials with correct identification.

### *Statistical analysis*

*Behavioral Data* While the distribution of errors did not differ from a Gaussian fit (Kolmogorov-Smirnov  $p > .200$  consistently), the distribution of reaction times differed ( $p < .001$ ) and they were logarithmically transformed obtaining a suitable fit ( $p > .200$  consistently). Log-transformed reaction times were analyzed by univariate general linear model (GLM) with *Logical Operator* (UNIVERSAL, PARTICULAR) and *Contradiction* (CONTRADICTION, NOT CONTRADICTION) as fixed factors and *Subject* as Random factor. Percentages of errors were submitted to an analysis of variance (ANOVA) for repeated measures with *Logical Operator* (UNIVERSAL, PARTICULAR) and *Contradiction* (CONTRADICTION, NOT CONTRADICTION) as within-subject factors. Absence of either *Logical Operator* or *Contradiction* main factor for Errors was checked, indicating that the accuracy in performing the tasks did not change in relationship to the presentation of the different sentences.

*Reasoning Network behavior* The dynamics of the RN-evoked response were submitted to statistical analyses to assess amplitude differences in different tasks. The mean

1  
2  
3 amplitude areas included between the onset of the early negative stage and the return to baseline  
4 and the positive stage onset and the return to baseline were considered for RN-evoked response,  
5 both following the premise and conclusion presentations. Since the distributions of these parameters  
6 did not differ from a Gaussian fit (Kolmogorov-Smirnov  $p > .200$  consistently), they were submitted  
7 to an analysis of variance (ANOVA) without correcting transformations. The full model included  
8 *Sentence* (PREMISE, CONCLUSION), *Logical Operator* (UNIVERSAL, PARTICULAR) and *Contradiction*  
9 (CONTRADICTORY, NOT CONTRADICTORY) as within-subject factors.

10  
11  
12 A result was reported only if it was statistically significant ( $p < .050$  Greenhouse-Geisser  
13 corrected whenever the sphericity assumption for ANOVA was violated).

## 20 21 RESULTS

### 22 23 *Behavioral Data*

24  
25  
26 Subjects performed the PARTICULAR and UNIVERSAL tasks with comparable accuracy both for  
27 the contradictory and not contradictory conditions, as demonstrated by the absence of any main  
28 **effect** from the ANOVA design for the number of errors ( $p > .200$ ) (Table 2).

29  
30  
31 On the contrary, reaction times showed a strong main *Logical Operator effect*  
32 [logarithmically transformed time  $F(1, 10.098) = 32.535$ ,  $p < .001$ , Table 2], with longer reaction  
33 times for UNIVERSAL tasks than for PARTICULAR ones. A *Contradictory* effect was not observed ( $p$   
34 = .441).

### 35 36 37 *Identification of Reasoning Network (RN)*

38  
39  
40 In every subject a single Independent Component (IC) was associated with an event-related  
41 response occurring at latencies subsequent to those traditionally associated with primary sensory  
42 processing (Fig. 2). This IC accounted for the majority of the variance of the whole non-artifactual  
43 scalp EEG signals along the whole 40 min session in each subject (Table 3, second column). As  
44 said before, we refer to this IC as the reasoning network (RN).

45  
46  
47 **Consistently across subjects**, the RN included the **bilateral Temporo-polar cortex** (middle  
48 temporal gyrus **Brodmann** Area (BA) 21 and the most rostral part of the superior and middle  
49 temporal gyri BA 38), the **bilateral Orbitofrontal cortex** (BA 10, 11 and 47) and the **bilateral**  
50 **Anterior Cingulate Cortex** (BA 32) (Fig. 3, Table 3).

### 51 52 53 *Reasoning Network Behavior*

54  
55  
56 At the presentation of the two sentences (Fig. 4 a, b), RN activated much more strongly after  
57  
58  
59  
60

the conclusion (mean  $1.62 \pm \text{s.d. } 0.69$  averaged over the 4 conditions) than the premise ( $1.33 \pm 0.53$ , paired t-test  $t(10) = -3.396$ ,  $p = .007$ ). Moreover, the processing of the conclusion lasted much longer ( $1663 \pm 651$  ms) than that of the premise ( $1233 \pm 454$  ms,  $t(10) = -3.842$ ,  $p = .003$ ). Remarkably, the RN activated much faster after the conclusion presentation ( $280 \pm 87$  ms) than after the premise ( $481 \pm 101$  ms,  $t(10) = 12.225$ ,  $p < .001$ ). This last feature underlines the fact that the reasoning for contradiction identification starts with the premise processing. On this basis, we developed the statistical modeling to include both premise and conclusion as a whole reasoning process.

As for the involved anatomical structures mentioned in the above section, the RN time-frequency characteristics were also highly consistent across subjects. RN dynamics consistently showed an early negative stage in the 150-500 ms time period after sentence presentation (Early Negative Stage) across trials (Fig. 5, first row). With a similar inter-trial stability, a positive stage was subsequently found reaching maximal amplitude between 500-2000 ms after appearance of both the premise and the conclusion sentences (Positive Stage). In terms of spectral characteristics, the RN activity was strongly represented in the 0.1-15 Hz frequency range (Fig. 5 second row). Moreover, a clear dynamic of oscillating activity in the gamma band was evident for the duration of the task (Fig. 5 second row).

*Early Negative Stage* Full model ANOVA did not display any main or interaction effect.

*Positive Stage* Full model ANOVA indicated clear interaction effects *Sentence\*Contradiction* [ $F(1,10) = 14.879$ ,  $p = .003$ ] and *Sentence\*Logical Operator* [ $F(1,10) = 5.854$ ,  $p = .036$ ], indicating that the reasoning network was activated in a different way during the presentation of the premise and the conclusion depending on the presence or absence of *Contradiction*, and whether a UNIVERSAL or PARTICULAR premise had to be contradicted. To better investigate the subtended phenomena, the two sentences were submitted to respective ANOVA reduced models.

*Premise* While a *Contradictory* effect was completely absent ( $p = .878$ ), a strong *Logical Operator* effect was found [ $F(1,10) = 10.616$ ,  $p = .009$ ], corresponding to a stronger reasoning network activation during the presentation of UNIVERSAL as opposed to the PARTICULAR sentences (Fig. 4c).

*Conclusion* A clear *Contradictory* effect appeared [ $F(1,10) = 7.402$ ,  $p = .022$ ], corresponding to a stronger reasoning network activation when the CONTRADICTORY conclusions were presented than when the NOT CONTRADICTORY ones were (Fig. 4d). *Logical Operator* effect

1  
2  
3 did not reach statistical significant ( $p = .193$ ).  
4  
5

6  
7 To investigate, in greater detail, dynamic properties of different stages of information  
8 processing, the RN activity periods during the presentation of premises and conclusions were  
9 subdivided into earlier ascending and later descending activation phases (Fig. 4 c, d), by  
10 introducing into the statistical design the corresponding within-subject factor *Phase* (ASCENDING,  
11 DESCENDING). The amplitude of RN activity was calculated as the mean area between activation  
12 onset and the maximum for the ascending phase, and between the maximum and the return to  
13 baseline for the descending phase.  
14  
15  
16  
17  
18

19 The analysis of the premise showed that the *Logical Operator effect* appeared only during the  
20 descending phase [ $F(1,10) = 5.148, p = .047$ ] (Fig. 4c).  
21  
22

23 The analysis of the conclusion showed, in addition to the above-mentioned *Contradictory*  
24 *effect*, the interaction *Phase\*Logical Operator* effect [ $F(1,10) = 4.942, p = .050$ ]. While RN  
25 activations did not differ during the ASCENDING phase, during the DESCENDING period UNIVERSAL  
26 conclusions induced stronger RN activation than PARTICULAR ones [reduced model in descending  
27 phase  $F(1,10) = 5.448, p = .042$ , Fig. 4 c, d].  
28  
29  
30  
31  
32

### 33 DISCUSSION

34  
35  
36  
37 Contradiction is a cornerstone concept in logic and is considered to be the basis for any  
38 reasoning process. In more general terms, contradiction is inherently associated with a ‘truth’  
39 criterion. Contradictory entities are present in every significant human experience as the two faces  
40 of a coin: light and darkness, joy and sorrow, passion and suffering, life and death. Our study on  
41 contradiction offers a novel angle to the discussion on a human reasoning aspect intimately  
42 connected with the historical tradition of mathematicians, philosophers and physicists and sheds  
43 light on a fundamental aspect of cognition.  
44  
45  
46  
47  
48  
49

#### 50 51 *RN activity Universal > Particular*

52  
53 During reasoning, in order to identify whether a conclusion contradicts a premise, our  
54 reasoning network shows a significantly greater activation when a UNIVERSAL statement is  
55 processed. The more limited computational load required to process PARTICULAR statements could  
56 be due to the more direct process required to explore a single example in the case of a ‘Some’  
57 sentence, as opposed to the multiple examples or the absence of a counterexample searched for  
58 during processing of an ‘Every’ sentence. The longer reaction times found for UNIVERSAL as  
59  
60

1  
2  
3 opposed to PARTICULAR statements seem to support this hypothesis (Table 2). When reasoning  
4 about familiar and concrete situations – as opposed to unfamiliar and abstract ones like ‘Every A is  
5 B ...’ – our brain automatically utilizes, in parallel with formal methods, situation-specific  
6 heuristics based on prior knowledge and experience (Goel et. al. 2007b). Previous evidence  
7 suggests that the response of the frontal–temporal system to familiar situations is – at least to some  
8 degree – content specific. In particular, the middle temporal lobe regions as part of object-based  
9 knowledge networks are more active when reasoning on statements like ‘Every tree is tall’ and  
10 were structures well represented in our reasoning network. In our experiment, when processing  
11 statements commonly encountered in natural language, the fronto–temporal system was challenged  
12 more by universal than particular forms. Our result **suggested** that in processing familiar sentences,  
13 generalization requirements recruit a wider network than would be required when assigning specific  
14 attributes within a limited field of action.  
15  
16  
17  
18  
19  
20  
21  
22  
23

24  
25 In spite of an identical inversion required by both logical operators, we found that universal  
26 sentences required stronger reasoning network activation than particular ones. This could be  
27 explained by a different internal representation of the logical operators themselves rather than by  
28 the effect of the applied rule.  
29  
30  
31  
32

### 33 *RN activity dynamics*

34  
35 The early negative stage of the reasoning network event-related dynamics (Fig. 4 and Fig. 5),  
36 peaking around 150-500 ms after sentence presentation in correspondence with the reading phase,  
37 was remarkably consistent with intra-cortical recordings from lateral prefrontal cortex during word  
38 reading (Lachaux et al. 2008). This seems to support the idea that the reading phase is parallel to  
39 cognitive processes possibly mediated by a coordinated interaction between regional  
40 synchronizations and desynchronizations of neuronal oscillations, reflecting long-range network  
41 engagement (Lachaux et al. 2008). This initial phase is followed by a strong positive stage lasting  
42 approximately 1.5 s when the presence of a contradictory conclusion is identified. This is associated  
43 with a consistent pattern of an ascending phase lasting about 300 ms and a successive decay starting  
44 at about 800-900 ms from sentence presentation. This latter phase corresponds to the period in  
45 which the logical operator is classified during premises and conclusions.  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55

### 56 *RN activity Contradictory > Not Contradictory*

57  
58 Subjects had to target the contradictory sentences and these evoked stronger reasoning  
59 network activation than the control not contradictory ones. As opposed to what is observed when  
60 comparing Universal and Particular sentences, reaction times were similar for contradictory and not

1  
2  
3 contradictory pairs, suggesting that the higher RN amplitude does not reflect a higher processing  
4 load during the identification of contradictoriness. The activated reasoning network partially  
5 overlaps with the cortical component of the central system sustaining decision-making, strongly  
6 involving the orbitofrontal and cingulate cortices. It has, in fact, been recently determined that, in  
7 addition to the striatum and dopamine systems, **activity in these region is predictive of** the choices  
8 of animals and people (Rushworth and Behrens 2008). In particular, **enhanced activity in the**  
9 **orbitofrontal cortex (OFC) is associated with risk-taking behavior** (Doya 2008). The anterior  
10 cingulate cortex (ACC) plays an important role in motivating subjects to act on the basis of a  
11 cost/benefit estimate (Denk et al. 2005) The ACC has a strong topographical specificity, with the  
12 gyral component implicated in social learning and the sulcal in reward-based learning (Rudebeck et  
13 al. 2006; Walton et al. 2002). In our experiment based on identifying contradictions, stronger sulcal  
14 ACC and OFC activities were found while deciding in favor of the required task. The feedback  
15 consequent to the positive and negative response was the same; the same behavioral response was  
16 required as a consequence of the decision and subjects performed with similar reaction times in  
17 both cases. The absence of any external feedback after the identification of the contradictory form  
18 suggests that neural structures can develop an intrinsic ability to enhance synchronization  
19 phenomena as a consequence of performing the required task, without the need of a reward from  
20 the external environment. Our data could be explained by hypothesizing that human cognitive  
21 structures involved in reward-based training and decision-making are able – as a result of  
22 reinforcement-based learning to intrinsically induce an activity that had previously been dependent  
23 on external reward during the learning process This internal ability is further supported by recent  
24 hypotheses of the rostral prefrontal cortex (PFC, approximating BA 10) as the key attention-  
25 switching structure focusing either on environmental stimuli, or by contrast, on self-generated or  
26 maintained representations (i.e. the ‘thoughts in our head’, ‘gateway hypothesis’, Burgess et al.  
27 2007).

### 28 29 30 ***RN constituted by ‘expected areas’***

31  
32  
33 We found reasoning network activation in every subject. This involved the temporo-polar,  
34 orbito-frontal and anterior cingulate cortices. Moreover, single trial analysis showed strong  
35 repeatability of network recruitment throughout the task performance, indicating a fundamental role  
36 of searching for contradiction in human reasoning. Cognitive neuroscience data are not in keeping  
37 with a unitary system being the basis of logical reasoning, suggesting instead a distributed system  
38 that includes dynamic reconfiguration of the fronto-temporal and anterior cingulate regions in  
39 response to specific tasks and environmental cues (Goel 2007a). Language structures are not  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3 included in the networks activated by our paradigm, probably because reasoning about familiar  
4 situations automatically utilizes situation-specific heuristics, mainly involving orbito–frontal cortex  
5 and inferior–middle temporal regions (Goel et al. 2007b). Since in all subjects a single component  
6 explained the majority of the signal power throughout the experiment, and very simple common  
7 words were used for the reasoning, it is conceivable that structures processing semantic-syntactic  
8 content were not significantly engaged.  
9  
10  
11  
12  
13

### 14 15 *RN identification procedure*

16  
17 Brain electric fields recordable from the scalp through EEG are macroscopic post-synaptic  
18 potentials created by clusters of apical dendrites of neocortical pyramidal cells firing synchronously  
19 (Nunez and Srinivasan 2006). The absence of any appreciable delay in the scalp sensor signals with  
20 respect to neural current dynamics and frequency components, such that quasi-static approximation  
21 of Maxwell equations holds throughout the whole spectrum of interest, strongly supports the  
22 superposition principle, according to which the relation between EEG scalp potentials and  
23 generating cerebral sources may be reasonably approximated by a system of linear equations  
24 (Sarvas 1987). Under these conditions the use of a blind source separation technique such as ICA  
25 seems most advantageous for identifying cerebral activities of interest. ICA decomposes the data  
26 into sources with independent time courses and scalp maps, without taking into account any  
27 information about head and cerebral current physics and geometry. ICA, combined with  
28 time/frequency analysis and trial-by-trial visualization, is able to recover components indexing  
29 physiologically distinct processes. Moreover, the complexity of networks sustaining reasoning<sup>1</sup>  
30 strengthens the suitability of source identification methods based on source dynamic behavior  
31 instead of the mere localization of their spatial properties.  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45

46 In conclusion, a consistent reasoning network was clearly identified in each healthy volunteer  
47 that involved the temporo-polar, orbito-frontal and anterior cingulate cortices. After an early  
48 negative period lasting about 500 ms, this network was more activated for about 1.5 s, when  
49 processing universal statements and contradictory conclusions. Simpler cerebral processing in the  
50 heuristic figuring of a single example instead of many, or searching for the absence of a  
51 counterexample, could be the reason why the logical operator ‘Some’ induced smaller reasoning  
52 network activation than ‘Every’. A self-generated reward system appeared to be present in adult  
53 humans, with the ability to resonate the recruited circuitry when a task is accomplished in the  
54 required form.  
55  
56  
57  
58  
59  
60

**ACKNOWLEDGEMENTS**

The authors wish to thank Prof. Vito Michele Abrusci and Prof. Claudia Casadio for their continuous support and for valuable comments and Dr. Paolo Roselli for scientific discussion.

**REFERENCES**

- Barbati G, Porcaro C, Zappasodi F, Rossini PM, Tecchio F (2004): Optimization of an independent component analysis approach for artifact identification and removal in magnetoencephalographic signals. *Clin Neurophysiol.* 115:1220-32.
- Beckmann CF, Smith SM (2004): Probabilistic independent component analysis for functional magnetic resonance imaging. *IEEE Trans. Med. Imag.* 23: 137–152.
- Burgess PW, Dumontheil I, Gilbert SJ (2007): The gateway hypothesis of rostral prefrontal cortex (area 10) function. *Trends Cogn Sci.* 7:290-8.
- Denk F, Walton ME, Jennings KA, Sharp T, Rushworth MF, Bannerman DM (2005): Differential involvement of serotonin and dopamine systems in cost-benefit decisions about delay or effort. *Psychopharmacology.* 179:587–596.
- Doya K (2008) : Modulators of decision making. *Nat Neurosci.* 11 :410-6.
- Ferree T, Luu P, Russel JS, Tucker DM (2001): Scalp electrode impedance, infection risk, and EEG data quality. *Clinical Neurophysiology.* 112:536-544.
- Goel V (2007a): Anatomy of deductive reasoning. *Trends Cogn Sci.* 11:435-441
- Goel V (2003b): Evidence for dual neural pathways for syllogistic reasoning. *Psychologica.* 32:301–309.
- Goel V, Dolan RJ (2001): Functional neuroanatomy of three-term relational reasoning. *Neuropsychologia.* 39:901- 909.
- Goel V, Dolan RJ (2003a): Reciprocal neural response within lateral and ventral medial prefrontal cortex during hot and cold reasoning. *Neuroimage.* 20:2314-2321 .
- Goel V, Dolan RJ (2004): Differential involvement of left prefrontal cortex in inductive and deductive reasoning. *Cognition.* 93: B109- B121.
- Goel V, Tierney M, Sheesley L, Bartolo A, Vartanian O, Grafman J (2007b): Hemispheric specialization in human prefrontal cortex for resolving certain and uncertain inferences. *Cereb Cortex.* 17:2245–2250.
- Goel V, Buchel C, Frith C, Dolan RJ (2000): Dissociation of mechanisms underlying syllogistic reasoning. *Neuroimage.* 12:504-514.
- Greene JD, Nystrom LE, Engell AD, Darley JM, Cohen JD (2004): The neural bases of cognitive conflict and control in moral judgment. *Neuron.* 44:389-400.

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

- Hyvärinen A, Karhunen J, Oja E. 2001. *Independent Component Analysis*. New York: Wiley.
- Hyvärinen A, Oja E (2000): Independent component analysis: algorithms and applications. *Neural Netw.* 13:411–430.
- Hyvärinen A (1999): Fast and robust fixed point algorithms for independent component analysis. *IEEE Trans. Neural. Netw.* 10:126–634.
- Jung TP, Makeig S, Humphries C, Lee TW, McKeown MJ, Iragui V, Sejnowski TJ (2000): Removing electroencephalographic artifacts by blind source separation. *Psychophysiology* 37:163–178.
- Kroger JK, Nystrom LE, Cohen JD, Johnson-Laird PN (2008) Distinct Neural Substrates for Deductive and Mathematical Processing, *Brain Research*, doi: 10.1016/j.brainres.2008.07.128.
- Lachaux JP, Jung J, Mainy N, Dreher JC, Bertrand O, Baciou M, Minotti L, Hoffmann D, Kahane P (2008): Silence is golden: transient neural deactivation in the prefrontal cortex during attentive reading. *Cereb Cortex.* 18:443-50.
- Luo J, Yuan J, Qiu J, Zhang Q, Zhong J, Huai Z (2008): Neural correlates of the belief-bias effect in syllogistic reasoning: an event-related potential study. *Neuroreport.* 10:1073-1078.
- Makeig S, Debener S, Onton J, Delorme A (2004): Mining event-related brain dynamics. *Trends Cogn Sci.* 8:204-210.
- Makeig S, Westerfield M, Jung TP, Covington J, Townsend J, Sejnowski TJ, Courchesne E (1999): Functionally independent components of the late positive event-related potential during visual spatial attention. *J. Neurosci.* 19:2665–2680.
- Makeig S, Westerfield M, Jung TP, Enghoff S, Townsend J, Courchesne E, Sejnowski TJ (2002): Dynamic brain sources of visual evoked responses. *Science.* 295:690–693.
- Newstead SE, Ellis C, Evans JStBT, Dennis I (1997): Conditional reasoning with realistic material. *Thinking and Reasoning.* 3: 49–76.
- Nunez PL, Srinivasan R. 2006 . *Electric Field of the Brain*, 2nd ed., New York: Oxford Univ Press.
- Pascual-Marqui RD (2002): Standardized low-resolution brain electromagnetic tomography (sLORETA): technical details, *Methods Find. Exp. Clin. Pharmacol.* 24D:5-12.
- Porcaro C, Coppola G, Di Lorenzo G, Zappasodi F, Siracusano A, Pierelli F, Rossini PM, Tecchio F, Seri S (2009): Hand somatosensory subcortical and cortical sources assessed by functional source separation: An EEG study. *Hum Brain Mapp.* 30: 660-74.
- Porcaro C, Zappasodi F, Barbati G, Salustri C, Pizzella V, Rossini PM, Tecchio F (2006): Fetal auditory responses to external sounds and mother's heart beat: detection improved by Independent Component Analysis. *Brain Res.* 1101:51-8.

- 1  
2  
3 Prado J, Kaliuzhna M, Cheylus A, Noveck IA (2008): Overcoming perceptual features in logical  
4 reasoning: an event-related potentials study. *Neuropsychologia*. 46:2629-37.  
5  
6 Prado J, Noveck IA (2007): Overcoming perceptual features in logical reasoning: a parametric  
7 functional magnetic resonance imaging study. *J Cogn Neurosci*. 19:642-57 .  
8  
9 Qiu J, Li H, Huang X, Zhang F, Chen A, Luo Y, Zhang Q, Yuan H (2007): The neural basis of  
10 conditional reasoning: An event-related potential study. *Neuropsychologia*. 45:1533-1539.  
11  
12 Rudebeck PH, Walton ME, Smyth AN, Bannerman DM, Rushworth MF (2006): Separate neural  
13 pathways process different decision costs. *Nat. Neurosci*. 9:1161–1168  
14  
15 Rushworth MF, Behrens TE (2008): Choice, uncertainty and value in prefrontal and cingulate  
16 cortex. *Nat Neurosci*. 4:389-97.  
17  
18 Salustri C, Barbati G, Porcaro C (2005): Fetal magnetocardiographic signals extracted by 'signal  
19 subspace' blind source separation. *IEEE Trans Biomed Eng*. 52:1140-2.  
20  
21 Sarvas J (1987): Basic Mathematical and Electromagnetic Concepts of the Biomagnetic Inverse  
22 Problem. *Phys Med Biol*. 32,:11-22.  
23  
24 Tucker DM (1993): Spatial sampling of head electrical fields: the geodesic sensor net.  
25 *Electroencephalography and clinical Neurophysiology*. 87:145-163.  
26  
27 Vorobyov S, Cichocki A (2002): Blind noise reduction for multisensory signals using ICA and  
28 subspace filtering, with application to EEG analysis. *Biol. Cybern*. 86:293–303.  
29  
30 Walton ME, Bannerman DM, Rushworth MF (2002): The role of rat medial frontal cortex in effort-  
31 based decision making. *J. Neurosci*. 22:10996–11003.  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

**Table 1 – Stimuli Example**

| <b>Logical operator</b><br><br><b>Contradictoriness</b> | <b>UNIVERSAL</b>                           | <b>PARTICULAR</b>                            |
|---|--|--|
|   | <b>CONTRADICTORY</b>                       | Every man is mortal<br>Some men are immortal |
| <b>NOT CONTRADICTORY</b>                                | Every man is mortal<br>Some men are mortal | Some men are mortal<br>Every man is mortal   |

An example of the 4 experimental conditions. ES-C: **UNIVERSAL - CONTRADICTORY**; ES-NC: **UNIVERSAL - NOT CONTRADICTORY**; SE-C: **PARTICULAR - CONTRADICTORY**; SE-NC: **PARTICULAR - NOT CONTRADICTORY**.

Table 2 – Behavioral data

| Logical operator<br>Contradictoriness | UNIVERSAL                    | PARTICULAR               |
|---------------------------------------|------------------------------|--------------------------|
|                                       | <b>Correct responses (%)</b> |                          |
| CONTRADICTORY                         | 98.0 ± 3.2                   | 97.5 ± 1.9               |
| NOT CONTRADICTORY                     | 97.9 ± 2.2                   | 98.5 ± 1.7               |
| <b>Reaction times (log s)</b>         |                              |                          |
| CONTRADICTORY                         | 2.74 ± 0.007<br>[550 ms]     | 2.69 ± 0.006<br>[490 ms] |
| NOT CONTRADICTORY                     | 2.71 ± 0.006<br>[513 ms]     | 2.70 ± 0.006<br>[501 ms] |

In each of the 4 experimental tasks, mean across subjects ( $\pm$  s.d.) of the percentage of correct responses and of the reaction times, i.e. the time between the question mark appearance and the subject response, after logarithmic transformation. In squared parenthesis the exponential inverse transformation of the mean is indicated to give an idea of reaction time dimension (ms).

**Table 3 – Structures involved in reasoning networks**

| Subject        | ICs<br>EV (%) | Temporo-polar<br>cortex |                | Orbitofrontal<br>cortex<br>(OFC) |                   | Anterior Cingulate<br>cortex<br>(ACC) |           |
|----------------|---------------|-------------------------|----------------|----------------------------------|-------------------|---------------------------------------|-----------|
|                |               | L                       | R              | L                                | R                 | L                                     | R         |
| AI             | 60            | 20; 21; 38              |                | 47                               |                   |                                       |           |
| AS             | 82            | 38                      | 21; 22; 38     | 10; 11; 47                       | 10; 11; 47        |                                       | 32        |
| CP             | 84            | 38                      | 21; 22; 38     | 11; 47                           | 11; 47            |                                       |           |
| DB             | 82            | 38                      | 20; 21; 22; 38 | 10; 11; 47                       | 10; 11; 47        | 32                                    | 32        |
| DF             | 38            | 21; 38                  | 20; 21; 38     |                                  |                   |                                       |           |
| ET             | 88            | 20; 21; 38              | 20; 21; 38     | 10; 11; 47                       | 10; 11; 47        | 32                                    | 32        |
| FS             | 56            | 21; 38                  | 38             | 10; 11; 47                       | 10; 11; 47        | 32                                    | 32        |
| GDL            | 41            | 38                      | 20; 21; 22; 38 | 11; 47                           | 11; 47            | 32                                    | 32        |
| LDL            | 62            | 21; 38                  | 21; 38         | 11; 47                           | 11; 47            | 32                                    | 32        |
| MTM            | 87            | 20; 21; 38              | 20; 21; 22; 38 | 11; 47                           | 11; 47            |                                       |           |
| SC             | 90            | 20; 21; 22; 38          | 20; 21; 22; 38 | 10; 11; 47                       | 10; 11; 47        | 32                                    | 32        |
| <b>Average</b> | <b>70</b>     | <b>21; 38</b>           | <b>21; 38</b>  | <b>10; 11; 47</b>                | <b>10; 11; 47</b> | <b>32</b>                             | <b>32</b> |

For each subject, the variance of the signal from all channels throughout the 40 min explained by the identified IC is expressed as percentage of the total variance (IC EV). Structures involved within the network are expressed by the corresponding **Brodman** areas classified by the anatomical site.

## FIGURE LEGEND

### Figure 1 – Experimental setup

The beginning of the trial was signaled by a “+” appearing in the centre of the screen for 1 s, followed by the presentation of the premise categorical proposition for 2.5 s. Thereafter the sentence disappeared for 0.5 s (Waiting period), followed by the presentation of the conclusion categorical proposition for 2.5 s. Then, a question mark appeared for 1.5 s, requiring the subject to press **one push button if the conclusion contradicted the premise and a different push button if the conclusion did not. If they were unable to make a clear choice, they were told to omit the response (i.e., to not push either button).** Finally, a feedback advised the subject whether any button had been pressed or not, with no indication about the correctness of the contradiction identification. ‘New Trial’ appearing on the screen advised the subject that the next trial was starting.

### Figure 2 – Reasoning Network Identification

For representative ICs in one paradigmatic subject, the criteria used to classify them as artifacts (upper panel) and cerebral sources (bottom panel) are shown. From the left column: an exemplificative segment of IC signal (Time Evolution), the average triggered by the premise presentation across all 200 trials (ERP); Single Trail image with each epoch including premise-conclusion pair represented in color code in the abscissa with successive epochs in the ordinate (ST); and the Time Frequency plot representing each time point in the abscissa, the color coded spectral content in the ordinate (TF), vertical solid lines indicate the presentation of each sentence, the dashed line the end of the premise; spatial distribution obtained by representing the corresponding IC weights (Topographic map); the probability density function of the IC signal (pdf) with the black line indicating the normal probability density, the values of kurtosis (K) and skewness (S) are provided. As the ICA procedure performs whitened preprocessing, each quantity is expressed in arbitrary unit (a.u.).

Among the artifacts, the ocular artifact is in the first row, the cardiac artifact is in the second and line power is in the third. Among IC classified as cerebral sources, that represented in the first row, the only one showing clear event-related activity later than 150 ms, was consequently selected as the Reasoning Network.

### Figure 3 – Reasoning Network position

Topography of the reasoning network, averaged across subjects, localized as described in the methods section on a standard model. It is to be noted that the potential distribution obtained by retro-projecting only one IC is time-invariant up to a scale factor, consequently, the subtending

1  
2  
3 current distribution shape is time-independent.  
4

#### 5 **Figure 4 – Reasoning Network Behavior**

6  
7 *a)* RN activity after Premise and Conclusion presentations during the time periods lasting [-0.5,  
8 2.5] s, 0 being the sentence presentation. *b)* The RN activity after Premise and Conclusion are  
9 superimposed to facilitate comparison of their dynamics.  
10

11  
12 *c)* RN activity compared during the UNIVERSAL (ES-C, ES-NC) vs. PARTICULAR (SE-C, SE-NC)  
13 premise-conclusion pairs. The grey areas indicate significant change between the two task groups.  
14

15  
16 *d)* As case *c)* for the Contradictory vs. Not Contradictory task comparison.  
17

#### 18 19 **Figure 5 – Reasoning Network time-frequency behavior**

20  
21 **Up:** Average across subjects of the topographical distribution of the electric potential generated by  
22 the RN. **Middle:** Average across subjects of single trail image as described in Fig. 2 showing the  
23 RN time evolution along the premise-conclusion presentations corresponding to the four  
24 experimental conditions. **Bottom:** Again for each of the four tasks, time frequency plot as described  
25 in Fig. 2, averaged across subjects and referred to as the 500 ms pre-premise period. The green  
26 color code represents values non-significantly differing from 0 using a bootstrap technique with  
27 threshold at  $p = 0.01$ . Note that different scales hold for the oscillatory activity amplitude in the two  
28 (0-30) Hz and (30-90) Hz frequency bands.  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

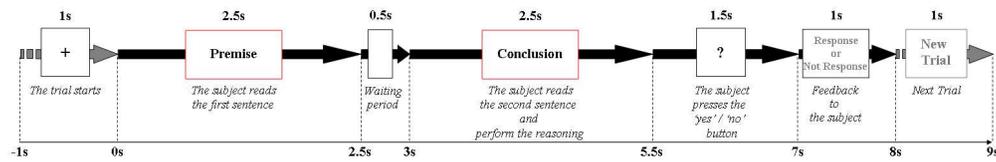


Figure 1 - Experimental setup

The beginning of the trial was signaled by a "+" appearing in the centre of the screen for 1 s, followed by the presentation of the premise categorical proposition for 2.5 s. Thereafter the sentence disappeared for 0.5 s (Waiting period), followed by the presentation of the conclusion categorical proposition for 2.5 s. Then, a question mark appeared for 1.5 s, requiring the subject to press one push button if the conclusion contradicted the premise and a different push button if the conclusion did not. If they were unable to make a clear choice, they were told to omit the response (i.e., to not push either button). Finally, a feedback advised the subject whether any button had been pressed or not, with no indication about the correctness of the contradiction identification. 'New Trial' appearing on the screen advised the subject that the next trial was starting.

409x69mm (96 x 96 DPI)

Peer Review

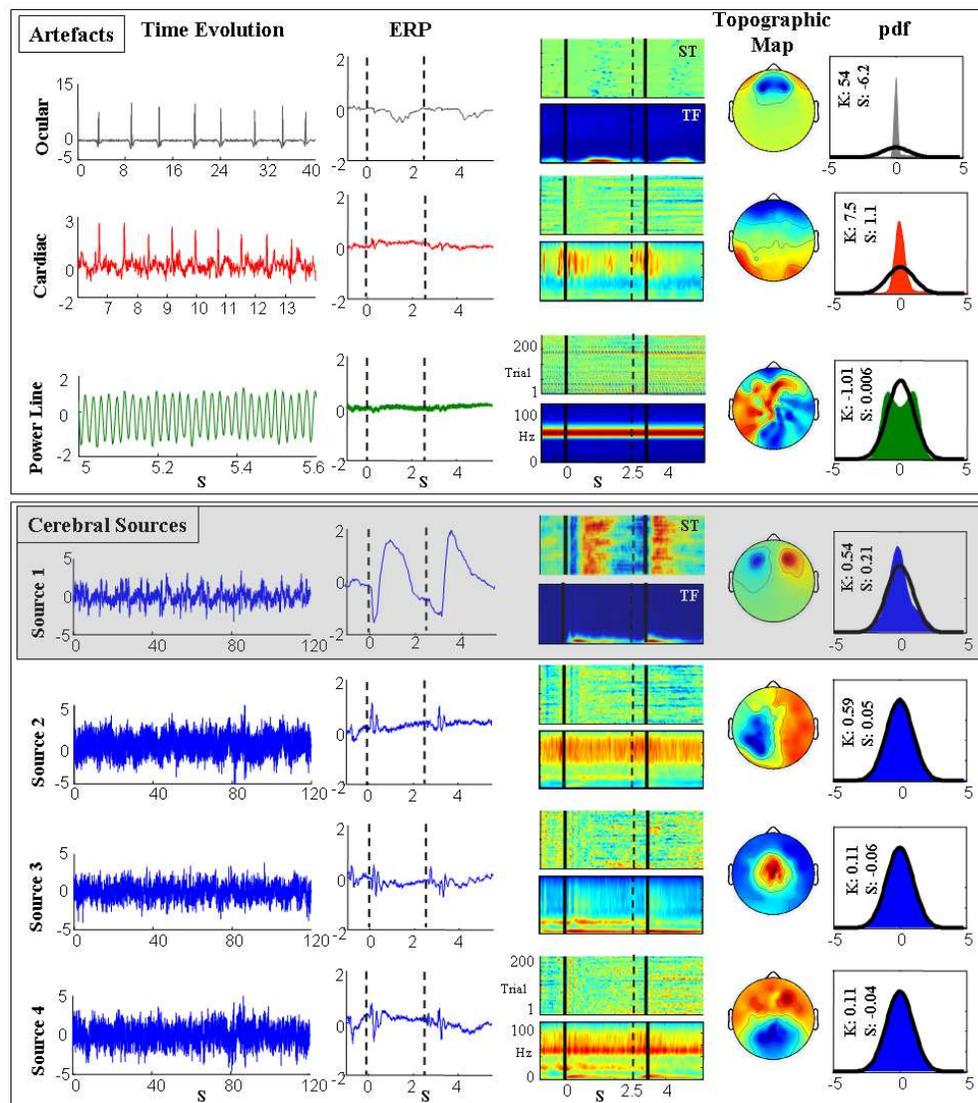


Figure 2 - Reasoning Network Identification

For representative ICs in one paradigmatic subject, the criteria used to classify them as artifacts (upper panel) and cerebral sources (bottom panel) are shown. From the left column: an exemplificative segment of IC signal (Time Evolution), the average triggered by the premise presentation across all 200 trials (ERP); Single Trail image with each epoch including premise-conclusion pair represented in color code in the abscissa with successive epochs in the ordinate (ST); and the Time Frequency plot representing each time point in the abscissa, the color coded spectral content in the ordinate (TF), vertical solid lines indicate the presentation of each sentence, the dashed line the end of the premise; spatial distribution obtained by representing the corresponding IC weights (Topographic map); the probability density function of the IC signal (pdf) with the black line indicating the normal probability density, the values of kurtosis (K) and skewness (S) are provided. As the ICA procedure performs whitened preprocessing, each quantity is expressed in arbitrary unit (a.u.).

Among the artifacts, the ocular artifact is in the first row, the cardiac artifact is in the second and line power is in the third. Among IC classified as cerebral sources, that represented in the first row,

the only one showing clear event-related activity later than 150 ms, was consequently selected as the Reasoning Network.

259x289mm (96 x 96 DPI)

For Peer Review

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

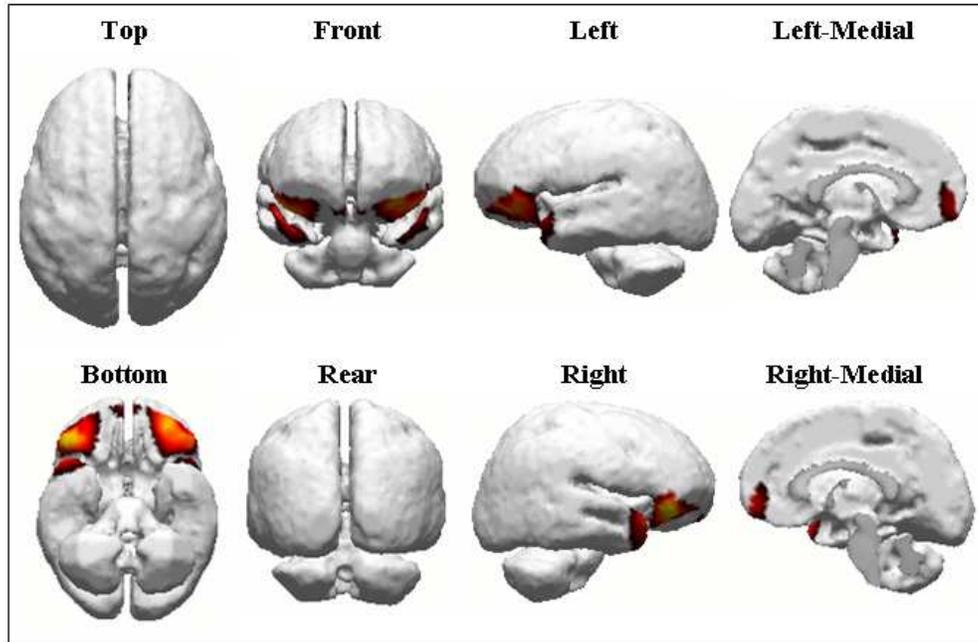


Figure 3 - Reasoning Network position

Topography of the reasoning network, averaged across subjects, localized as described in the methods section on a standard model. It is to be noted that the potential distribution obtained by retro-projecting only one IC is time-invariant up to a scale factor, consequently, the subtending current distribution shape is time-independent.

179x119mm (96 x 96 DPI)

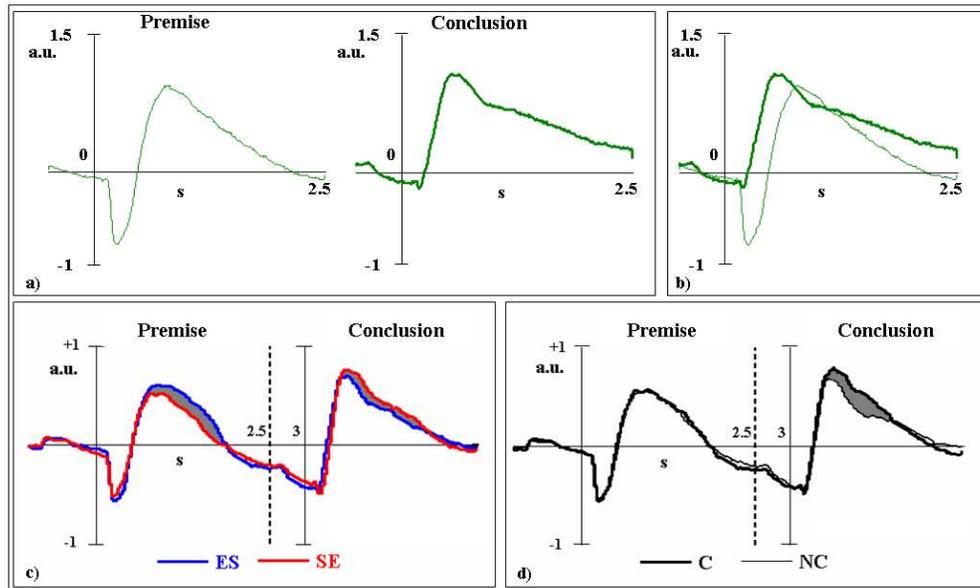


Figure 4 - Reasoning Network Behavior

- a) RN activity after Premise and Conclusion presentations during the time periods lasting  $[-0.5, 2.5]$  s, 0 being the sentence presentation. b) The RN activity after Premise and Conclusion are superimposed to facilitate comparison of their dynamics.
- c) RN activity compared during the UNIVERSAL (ES-C, ES-NC) vs. PARTICULAR (SE-C, SE-NC) premise-conclusion pairs. The grey areas indicate significant change between the two task groups.
- d) As case c) for the Contradictory vs. Not Contradictory task comparison.

277x169mm (96 x 96 DPI)

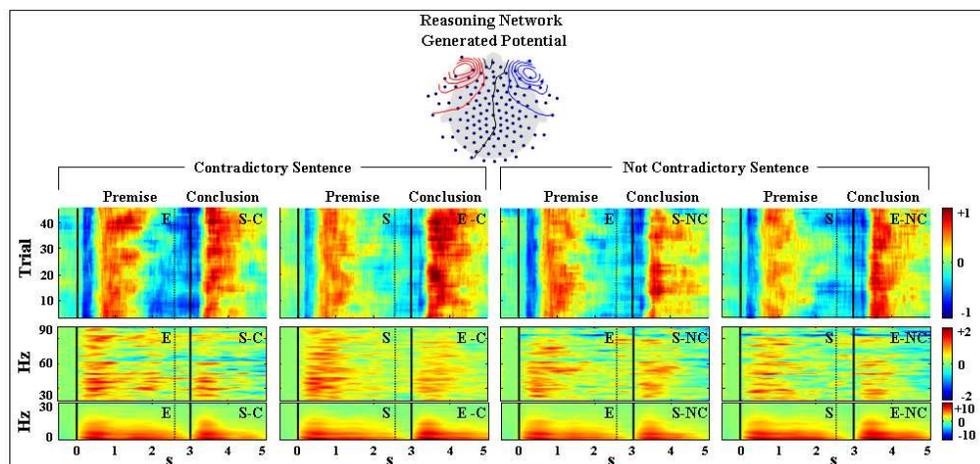


Figure 5 - Reasoning Network time-frequency behavior

Up: Average across subjects of the topographical distribution of the electric potential generated by the RN. Middle: Average across subjects of single trial image as described in Fig. 2 showing the RN time evolution along the premise-conclusion presentations corresponding to the four experimental conditions. Bottom: Again for each of the four tasks, time frequency plot as described in Fig. 2, averaged across subjects and referred to as the 500 ms pre-premise period. The green color code represents values non-significantly differing from 0 using a bootstrap technique with threshold at  $p = 0.01$ . Note that different scales hold for the oscillatory activity amplitude in the two (0-30) Hz and (30-90) Hz frequency bands.

269x129mm (96 x 96 DPI)