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Aristotelian vs. Paradoxical Reasoning Elicit Distinct N400 ERPs

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Abstract: There has been a growing interest in understanding the cognitive processes that underlie human reasoning. Since the N400 component of event related potentials (ERPs) represents the semantic integration of information processing, the present study focuses on the N400 elicited during processing of valid Aristotelian syllogisms vs. Zeno-like paradoxes. Fifty-one healthy participants (28 males, 23 females) were investigated while performing reasoning tasks based on either valid statements or paradoxes, adjusted to induce working memory (WM). The N400 waveform was recorded while the premises / conclusions of each statement were maintained in WM. Analysis revealed that Zeno-like paradoxes elicited a more negative N400 deflection than did valid syllogisms, at a distributed scalp topography with a propensity towards posterior abductions. These results suggest that Aristotelian and paradoxical logic engage distinct electrophysiological semantic processing as reflected by the N400 ERP component.

Keywords: Aristotelian, Event Related Potentials, N400, Paradoxes, Reasoning, Semantic, Zeno

1. Introduction

Reasoning plays a central role in science, society and the solution of practical problems. Without it, there would be no science, mathematics, logic, laws or principles in general [1].

Deductive reasoning, or Aristotelian syllogism, is the ability to draw conclusions from previous items of knowledge. Syllogisms involve two premises and one conclusion: "*All men are animals. All animals are mortal. Hence, all men are mortal.*" [2, 3].

In juxtaposition to this, about 2500 years ago Zeno the Eleatic conceived some syllogistic paradoxes, utilizing the method of indirect proof or *reductio ad absurdum.* These paradoxes have amazed philosophers and mathematicians alike, highly influencing subsequent research [4, 5, 6, 7]. An example would be: "*A moving arrow occupies a certain space at each instant. But, when an object occupies a specific space, it is motionless. Therefore, the arrow cannot simultaneously move and be motionless.*"

Recently we hypothesized that, beyond philosophical speculation on the violation of the norms of rational thought embedded in these paradoxes, this violation may also be detectable on a psychophysiological level of analysis [4, 8]. Accordingly, we compared the P300 component of event related potentials (ERPs) elicited during processing of valid Aristotelian syllogisms to that elicited during processing Zeno-like paradoxes. Both types of syllogism were presented in a way designed to engage working memory (WM) operation [9]. During paradox processing, we noted a more positive event-related potential deflection (P300) across frontal regions, whereas processing of valid statements was associated with noticeable P300 amplitudes across parieto-occipital regions. Based on these results we concluded that paradoxes mobilize frontal attention mechanisms, while valid deduction promotes parieto-occipital activity associated with attention and/or subsequent memory processing. This conclusion can be extended by previous observations linking P300 with a frontal location to the initial allocation of attention, while P300 with a posterior location has been related to activation comparing of perceived stimulation with the attentional and /or working memory operation [10, 11].

Furthermore, converging behavioural evidence indicates that the semantic aspects of problems significantly influence reasoning performance [12, 13]. One component of the ERPs that might be particularly informative in this context is the N400. The N400 has consistently been interpreted as a semantic processing index, the amplitude of which is modulated by processing costs attributed to building the greater sentence meaning [14]: the easier the semantic processing the lower the amplitude of the N400 [15]. Previous studies have confirmed the semantically-associated effect on N400 across different logical experiments. For example a recent study where participants were instructed to read texts containing either confirming or contradicting arguments, reports higher N400 amplitudes in incongruent than in congruent trials [16]. Similarly, a spatial reasoning ERP study found that a three-dimensional condition, as compared to a two-dimensional one, elicited an increased N400 amplitude, indicating that higher brain activity in the right frontal brain regions related with the integration and maintenance of spatial information in working memory for reasoning [17]. Likewise, ERP responses to consistent vs. inconsistent analogies showed that inconsistent analogies evoked enhanced N400 waveforms taken to reflect a delayed perceptual mismatch with semantic strategies [18]. Ferguson, Cane, Douchkov, & Wright [19] reported that the N400 waveform was more negative-going for belief-inconsistent vs. belief-consistent critical words. Finally, Blanchette & El-Deredy [20], using ERPs to investigate logically valid vs. logically invalid conditional reasoning, reported that valid and invalid conditions modulated the N400 component, which suggests the involvement of a semantically-based inferential mechanism common across different logical forms, content types and linguistic features of the problems.

In the context of this evidence, the aim of the present study was to explore semantic processing elicited by valid deductive reasoning and Zeno-like paradoxes in a healthy population, using the N400 ERP component in a design engaging WM operation. At this point it should be noted that WM refers to the ability to retain information "on line" in order to facilitate an ongoing task [21, 22]. A number of studies suggest a close relationship between WM functioning and reasoning ability [23-25].

We predicted that, due to increased ambiguity, reasoning of paradoxical statements would be associated with an enhanced N400 waveform relative to reasoning of Aristotelian syllogisms. To our knowledge, this is the first study to examine the electrophysiology of semantic processing as reflected by N400 component in the processing of Aristotelian and paradoxical logic.

2. Materials and Methods

2.1. Participants

This study was approved by the Ethics committee of University Mental Health Research Institute (UMHRI). A number of fifty-one healthy subjects (aged 33.9 years in average, standard deviation: 9.2; 28 males) participated in the experiment. All participants gave written consent, after being extensively informed about the procedure. They all had normal vision and no one had neurological or psychiatric history.

2.2. Stimuli and Procedures

2.2.1. Stimuli

The experiment was designed to juxtapose two mental functions: processing of syllogisms characterized as “valid” vs. processing of “paradoxical” reasoning. This was done by exposure of the participants to two arrays of statements, one containing 39 valid syllogisms, the other 39 paradoxes. The order of presenting the valid and paradoxical sections was counterbalanced across participants. The full arrays of valid and paradoxical statements used are available in a supplemental file submitted to the journal. Two indicative examples follow: the valid array included statements of the following type: “*All men are animals. All animals are mortal. Hence, all men are mortal.*” [26]. The paradox array consisted of statements of the following type: “*A moving arrow occupies a certain space at each instant. But, when an object occupies a specific space, it is motionless. Therefore, the arrow cannot simultaneously move and be motionless.*” (Aristotle, Physics VI: 9, 239b5) [27].

2.2.2. Behavioural Procedure

Each participant was seated comfortably 1 m away from a computer monitor in an electromagnetically shielded room. He / she was verbally instructed through the intercom to read carefully each statement which would appear in the monitor, followed by the question “Right OR Wrong?” and state verbally, after two presentations of a warning sound (a) whether the statement was right or wrong and (b) how certain, on a scale of 0 (not at all certain) to 100 (absolutely certain) he/she was of the answer. This verbal instruction was followed by two examples of valid and two of paradoxical statements as a training exercise ensuring that the participant had fully comprehended the task. After 2 min. of rest, he/she was instructed to initiate the formal experimental session by pressing the SPACE bar.

Once the participant initiated the procedure, the sequence of statements forming a valid or paradoxical reasoning proposition was presented on the screen. Each statement remained on the screen for a duration determined by the number of digits included in the sentence (see Table 1) and then was replaced by a blank screen for a period of 1000 ms. This was followed by a 500 Hz auditory warning stimulus of 65 dB and 100 ms duration, which was repeated after 900ms. The participant's verbal response and degree of confidence in the answer to each statement was recorded by an observer seated outside the experimental chamber.

The onset of the next statement followed completion of the previous verbal responses after a variable interval of 4 to 9 sec in order to avoid habituation with temporal test sequences.

2.2.3. Electrophysiological Procedure

Before entering the electromagnetically shielded test room, the participant was fitted with a cap equipped with 30 scalp electrodes and 2 reference potential electrodes, each attached to an ear lobe (see details of electrode placements in Section 2.3 and Figure 1). Through these electrodes, EEG was recorded for 1000msec before the first warning stimulus (EEG) and for 1000msec after that (ERP).

A summary of the behavioural and electrophysiological events sequence of the procedure is presented in Table 1.

Table 1. *Precise sequence of phases of the performed experiments.*

Sequence of actions	Duration of actions
Valid or paradox sentence (visual presentation)	Duration according to the numbers of the letters in the sentences e.g. a sentence involving 92 letters presented 11.04sec
EEG recording	1000ms
Warning stimulus	100ms
ERP recording	1sec
Warning stimulus repetition	100ms
Response onset	Within 5sec
Period between response completion and onset of next sentence presentation	4-9sec

2.3. Experimental Setup and Recordings

A Faraday cage was used in order to eliminate any electromagnetic interference that could affect the measurements; the attenuation of the mean field was more than 30dB. 30 scalp Ag/AgCl electrodes were employed to record the electroencephalographic (EEG) activity in accordance with the International 10-20 system of electroencephalography [28]. A map of the electrode constellation is shown in Figure 1. Two electrodes, each attached to an ear lobe, served for obtaining the reference potential.

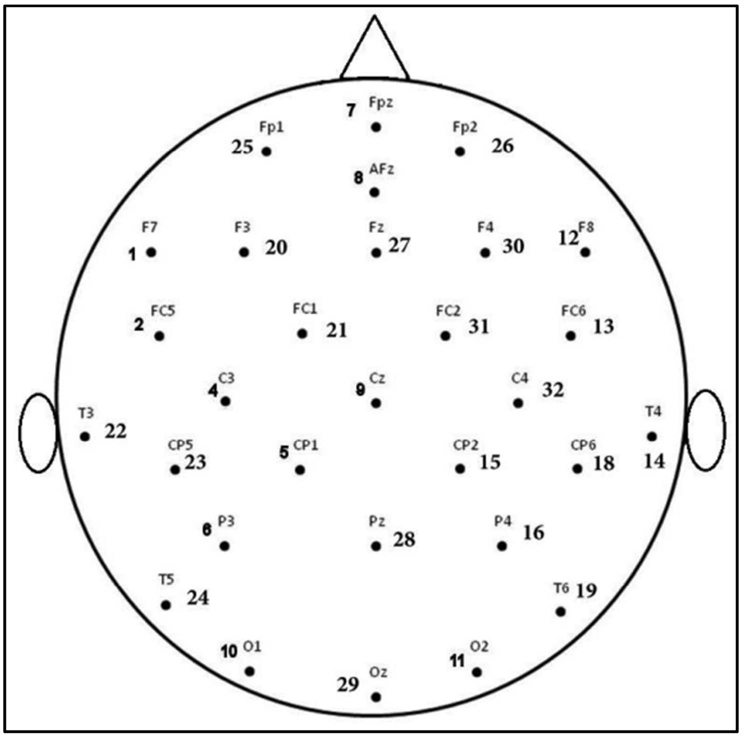

Figure 1. *Map showing the position of the ERPs' electrodes.*

Recordings with EEG higher than 75μV were excluded. Electrode resistance was kept constantly below 5kΩ. The bandwidth of the amplifiers was 0.05-35Hz, in order to avoid interference due to the power supply network's signal, which is at 50Hz. Eye movements were recorded by means of an electro-oculogram (EOG). The brain signals are amplified by a Braintronics DIFF/ISO-1032 amplifier before entering a 32-bit analogue to digital converter (NI SCB-68) which has a GPIB output. The digitized signal comprised an input for a Data Acquisition Card. The PC with the DAQ Card runs a LabView program for the recording of the signals, which can be monitored by an on-screen graphical representation. The evoked bio-potential signal was digitalized at a sampling rate of 1 KHz. The signals were recorded for a 2,000 msec interval, namely 1,000 msec before the first warning stimulus (EEG) and 1,000 msec after that (ERP).

For each question and for each electrode separately, 2,000 samples (expressed in μV) have been recorded in 2sec; evidently, the employed sample period was 1ms. For each question separately, we averaged the values of the EEG, namely the data acquired in the 100ms before the first sound stimulus.

We subtracted the obtained average from the initial signal, thus obtaining a translated version of the specific ERP recording. Thereafter, for the ERP detection, a Continuous Wavelet Transform (CWT) algorithm was developed, using EEGlab, running under Matlab® 2013 (MathWorks, USA), along with the Wavelet Toolbox™ [29]. Specifically, the complex Morlet wavelet was chosen as a mother wavelet, which is generally considered to be ideal for biological signal processing [30]. The algorithm followed is comprehensively described in [9].

The wavelet coefficients obtained by analyzing and reconstructing the evoked potential were considered via conventional averaging in each participant. Based on these coefficients, an appropriately scaled wavelet was chosen to match the N400 component. The wavelet was convolved with the EEG signals, only in the corresponding part of the signal where the N400 component could be situated (300-500 ms after the trigger onset), thus avoiding a false ERP detection. ERP peak values and corresponding latencies were extracted for each EEG channel of each participant, for each condition.

2.4. Statistical Analysis

2.4.1. Electrophysiological Data

The amplitudes and latencies of the N400 component taken over the range of 300-500 ms were subjected to paired t-test analysis.

The STATISTICA 10.0 for Windows (Statsoft Inc. Tulsa, OK, USA) software was used to assess the statistical significance of the observed differences between the Valid and Paradoxes measurements by means of a standard t-test for related samples (repeated measures). Due to the multiple comparisons, the Bonferoni correction was applied to all p-levels.

2.4.2. Behavioural Data

Behavioural responses were coded as follows: for the 39 valid statements "Right" was considered the correct answer whereas for the 39 paradoxes "wrong" was considered correct (responses coded as 0 and 1 for incorrect and correct responses respectively, and the total of correct responses is presented for each condition. Total accuracy per condition was expressed as the proportion of correct answers per 39 opportunities. The average confidence of each subject about his or her judgments is also presented in the form of a percentage.

3. Results

The analysis revealed a statistically significant higher amplitude of the N400 component during the paradox condition as compared to the valid one at leads P3, P4, CP6, T5, T6, O1, O2, and Oz (See Table 2). There were no differences in the latencies of N400 waveforms between the two experimental conditions.

Table 2. *Mean values and standard deviations of the N400 amplitudes in μV for Aristotelian and paradoxical reasoning, at the abductions where statistically significant differences were obtained (p <0.50).*

Amplitudes	Valid	Paradoxes	p (after Bonferroni correction)	partial η^2	power
P3	-0.922 (0.17)	-1.464 (0.18)	0.021023	0.182	0.906
O1	-0.420 (0.23)	-1.403 (0.20)	0.000496	0.291	0.993
O2	-0.270 (0.21)	-1.419 (0.20)	0.000143	0.336	0.999
P4	-0.760 (0.17)	-1.530 (0.15)	0.002534	0.247	0.978
CP6	0.986 (0.72)	-1.638 (0.59)	0.000955	0.169	0.879
T6	-0.465 (0.17)	-1.186 (0.18)	0.014912	0.186	0.912
T5	-0.759 (0.19)	-1.486 (0.22)	0.036728	0.141	0.801
Fz	-0.079 (0.37)	-1.378 (0.33)	0.008569	0.167	0.875
Oz	-0.343 (0.29)	-1.255 (0.18)	0.006077	0.166	0.870

As seen in Table 2 above, partial η2 (eta squared) values were large for all comparisons (suggested norms for partial η2: small = 0.01; medium = 0.06; large = 0.14).

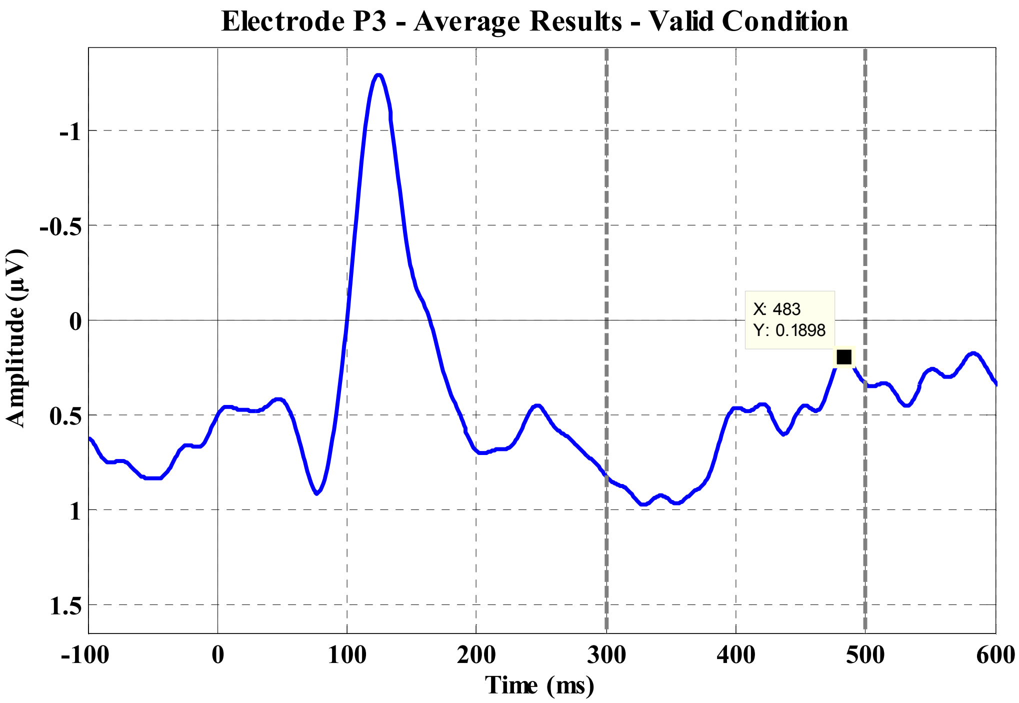

Figure 2. *Grand ERP waveform in microvolts, for the valid condition at lead P3.*

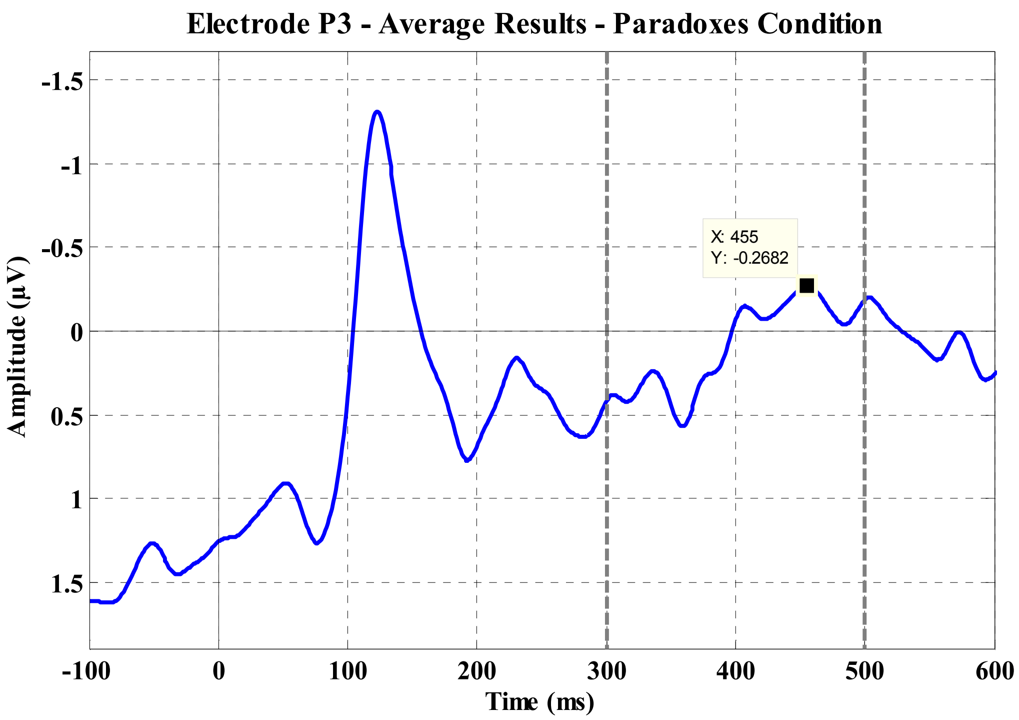

Figure 3. *Grand ERP waveform in microvolts, for the Paradoxes condition at lead P3.*

3.1. Behavioural Results: Comparison of Response Accuracy and Confidence Between the Two Conditions

The comparison of response of accuracy and confidence revealed statistically significant (paired t-test $t=10.67$, $p=0.00$). In particular, the mean correct response in the valid condition (judgement = "right") were higher than those obtained in the paradoxes (judgement = "wrong"; 29.25 and 19.49 respectively). Additionally, it was found that the self-rated confidence of the valid condition was significantly higher compared the paradoxes one (means 82.14 and 77.43 respectively, paired t-test: $t=4.08$, $p=0.00$).

Table 3. *Response accuracy and confidence for the Valid and Paradoxical conditions*

	Mean	**Std.Dv.**	**N**	**Diff.**	**t**	**df**	**p**	**-95%**	**+95%**
Score Valid	29.26	5.65							
Score Paradox	19.49	5.45	51	9.77	10.67	50	0.000	7.93	11.60
	Mean	Std.Dv.	N	Diff.	t	df	p	-95%	+95%
Confidence Valid	82.14	11.16							
Confidence Paradoxes	77.43	13.55	51	4.71	4.08	50	0.000	2.39	7.03

3.2. Correlations Between Electrophysiological and Behavioural Data

The analysis did not found a correlation between behavioural performance and the N400 waveform.

4. Discussion

This study compared brain activation patterns while participants maintained the premises / conclusions of either a valid syllogism or a paradoxical statement in working memory (WM). The N400 of ERPs was recorded in the WM phase, during which participants were instructed to draw a logical conclusion regarding the correctness of the valid syllogisms or the paradoxes. The electrophysiological data demonstrated a more negative N400 deflection under the paradoxes condition, with a distributed scalp topography. The differences were located at leads P3, P4, CP6, T5, T6, O1, O2, and Oz. There were no differences in the latencies of N400 waveforms between the two experimental conditions.

Regarding the behavioural performance it was found that both accuracy and self-rated confidence of the valid condition were significantly higher compared to those in the paradoxes condition.

As proposed in our hypothesis, paradoxes evoked more enhanced N400 waveform than Aristotelian logic. This is in line with previous studies presented in the Introduction, where increased ambiguity, as in incongruent trials vs. congruent trials, induced higher N400 amplitudes. Kutas and Federmeier [14] postulated that the N400 waveform reflects integration of the semantic meaning of a count held in working memory. In this framework, the integration of a semantically incongruent count is more effortful than the integration of a congruent one, thereby eliciting greater N400 amplitudes. Moreover, N400 would be expected during the execution of complex tasks involving semantic strategies [31, 32], with its amplitude being modulated by the endeavour of the semantic integration [33, 34, 14]. Moreover, Szucs & Soltész [31] suggested that mismatch trials in the semantic task could also elicit an obvious N400 component. Several studies have indeed reported that N400 was elicited in complex perceptual mismatch tasks. For example, Wang et al. [35] found that a condition of perceptual mismatch evoked larger N400 than a perceptual match condition, when subjects were required to attend to two dimensions (shape and colour). Similarly, Bennett et al. [32] found that a perceptual mismatch condition evoked larger N400 than a perceptual match condition when task-irrelevant distractors were added in a delayed matching-to-sample task. Furthermore, the N400 waves elicited by the mismatch condition with distractors were more negative than in the task without distractors.

Thus, the N400 observed in the present study may be modulated by semantic relationships between stimuli (for reviews see [34, 14]). The more effortful it is to integrate the semantic relationships, as in the condition of paradox processing, the larger the N400 amplitudes would be expected to be [33, 34, 14].

In summary, the N400 has been shown to be elicited consistently in a number of tasks as a product of semantic integration. Additionally it shows a broad distribution, typically with a centro-parietal maximum [14].

However, in the present study we also obtained both frontal and occipital distribution of the N400 effect. A frontal distribution of N400 has been observed in certain studies [36, 37]. An increased N400 peak amplitude within the fronto-central cortical areas was shown in response to incongruous sequences in patients and controls [36].

Furthermore, there are studies reporting N400 potentials at occipital areas in association with contextual semantic manipulations. An example is a study designed to investigate how and when accentuation temporally influences selective attention and subsequent semantic processing during on-line spoken language comprehension, and how this accentuation effect changes in response to the degree of accentuation [38]. Semantically incongruent words elicited a parietal–occipital N400 effect under the accentuation condition compared to semantically congruent words. In line with this finding, a study simultaneously using EEG and fMRI analysis to compare face recognition of famous and vs. unfamiliar faces, obtained a N400 effect, the source reconstruction of which was in the occipital gyri bilaterally [39].

The cortical areas activation of which appears to be involved in semantic processing provide key insights into the phenomenon. These areas have been grouped into three broad categories: posterior multimodal and heteromodal association cortex, heteromodal prefrontal cortex and medial limbic regions [40].

Recent studies, using fMRI and TMS, which manipulated the representational and control demands of a semantic task, found specific subregions of a brain network associated with knowledge of actions, manipulable artefacts and abstract and concrete concepts. For example, it has been shown that the anterior temporal lobes (ATL) were sensitive to the number of meanings retrieved, while the posterior middle temporal gyrus (pMTG) and the left inferior frontal gyrus (LIFG) showed effects of semantic selection. Moreover, LIFG and pMTG produced equal disruption of tasks tapping semantic control [41]. Along these lines, contemporary neurosurgical models of language organization suggest that semantic information is carried out in a ventral pathway that runs from the temporal pole to the basal occipitotemporal cortex, with anterior connections [42].

The absence of differentiation of our two experimental conditions with respect to N400 latencies is compatible with the view that the latency of this ERP component is relatively stable [14].

Relationships noted between our psychophysiological and behavioural datasets deserve comment. The decreased response accuracy noted under paradoxical processing is in line with reports of reasoning performance fluctuations according to cognitive load. Cognitive load impairs reasoning performance [43]. Performance is significantly better on reasoning tasks where the value of a conclusion (true or false) coincides with the logical relationship between premises and conclusion, valid or invalid [44, 45].

In this context, it was unexpected that we detected no correlations between behavioural performance and the N400 waveform. This discrepancy may reflect a need for more sensitive behavioural indices than accuracy and confidence, such as response latency. However, it is more likely to indicate a superior capacity of psychophysiological measures to access endophenotype, that is "the manifestation of a disorder via anomalies not observable by diagnostic interviews or traditional psychological measures" [46].

4.1. Limitations

The main disadvantage of the sentence-based research practice is confounding due to the interaction between reasoning-related brain activity and higher level linguistic processing. A further disadvantage of this practice is that it ignores instances of reasoning based on non-linguistic inputs and information received directly from the senses. It is, of course, essential to extend the present approach to other reasoning tasks. In spite of these limitations, our study suggests a potential role for the obtained patterns of N400 in the reasoning process, which may provide insights in the cortical engagement underlying detection of paradoxical reasoning and the successive appraisal / update of mental representations.

4.2. Conclusions

This study compared reasoning operations while the same participants, within the same experimental paradigm, engaged in deductive vs. paradoxical reasoning. This design removes confounds introduced by differences in paradigms, stimuli and participants, which could account for some of the inconsistencies in specific activations reported in previous neuroimaging experiments (e.g. [47, 48]).

We demonstrated that these two reasoning processes engage distinct neurocognitive processing towards the construction of meaning, as reflected by N400 effects distributed at fronto-parieto-occipital areas. The study can provide insights regarding the functional roles of distributed brain systems in human deductive reasoning on the basis of N400 ERP component. Our results also indicate that the use of ERP methodology may provide a step forward in elucidating and understanding mechanisms underlying important brain responses under conditions difficult to capture through behavioural settings.

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