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GAZE PATTERNS OF COMPOUND NEGATION PROCESSING

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Abstract

The aim of this study is to describe some key components of the relation between reasoning and gaze behaviour. Specifically, we studied gaze dwell and fixations during a sentence-equivalence task that required the processing of compound negation for conjunctions and disjunctions. We derived opposite predictions from two different theories of reasoning. The Mental Models Theory was tested against the formalist PSYCOP theory. The former predicts specific patterns of inspection times and gaze fixations frequency as functions of representational complexity and semantic depth. That is, the more complex representation is, and the deeper the meaning processing is, the longer inspection times and the higher fixations frequency should be. PSYCOP predicts the opposite visual behaviour pattern or no difference at all. We tested such predictions experimentally using eye-tracking technology. Our results support the Mental Models Theory. That is, it seems that human mind constructs mental models to process the negation of conjunctions and disjunctions according to eye-tracking evidence.

Keywords: *Vision-gaze-fixation-reasoning-negation*

How We Reason?

Many decades of theoretical and empirical research on human reasoning suggests that we reason by means of imagination [1]. That is, we construct and manage mental representations of possibilities associated to the available information [2]. It seems that we activate such mental resources to infer conclusions from a given set of statements, to solve problems, and to make decisions [3]. From this perspective, the Mental Models Theory -or model theory for short- has developed an articulated account concerned with deductive reasoning [4]. The model theory suggests that we build mental models to think, that is, we construct simplified cognitive representations of the world [3]. Since such representations require the active participation of working memory, some empirical variables like response times and eye behaviour can be considered relevant to test experimental hypotheses derived from the model theory [5,6,7]. When higher the working memory load is, the longer the response times would be. Similarly, more eye movement can be predicted when the working memory demand becomes higher [8].

Some alternative theories have been proposed to account for human reasoning [3]. Two sets of them can be considered particularly influential: Dual-Processing theories and formalist theories [4]. The former set of theories suggest that we think in the context of two systems of cognition, or more directly, that we have two minds, an intuitive mind and a reflective mind [9]. Such heuristic-analytic view has made many important contributions to the current understanding of deductive reasoning [4]. In particular, the Dual-Process perspective has found prominent reasoning biases, which can be understood as automatisms, rapid and distorted thoughts that occur beyond our conscious control. One example of such phenomena is the matching bias response in the Wason

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Selection Task [10]. Briefly described, a matching bias occurs when a shallow process replaces the sound representation of a deduction [4]. Hence, a superficial matching between a prime and a target drives the production of a conditional reasoning. This phenomenon has been profusely replicated and seems to be ubiquitous [11]. In previous studies, we found matching-bias-like phenomena concerned with compound reasoning focused on the negation of a conjunction and the negation of a disjunction [5,11]. The other prominent set of reasoning theories is rooted on a Piagetian intuition: the rules of logic shall be written in our minds [12]. Therefore, under certain conditions, the sound reasoning shall be universally available [4]. Probably, the most influential of such theories is the formalist account known as PSYCOP, that is, the Psychology of Proof proposed by Lance J. Rips [13,14,15]. According to PSYCOP, human thinking requires two hard translations that surround mental computation *per se*. That is, a first translation might operate on the noisy information entered to the mental system. The input should be perceptual, the product shall be a series of internal propositions that work like lines of code inside a computer language. After processing such code, the resulting inference might require a second translation from the mental language back to the noisy natural language. PSYCOP can be considered as an important account because some empirical predictions can be derived from its codes [13]. However, it seems to be less interesting when its proponents undermine the possibility of empirical testing by arguing that both translations are almost incompatible with experimental inspection [4].

Mental Models of Compound Negation

In 2012, Khemlani, Orenes, and Johnson-Laird proposed an extension of the model theory to specifically account for negation, its meaning, representation, and use [16,17]. Formally, negation is a logical operation that inverts the truth value of a given proposition [18,19]. For example, let *p* be a true proposition such that *p* states “London is a city”. The negation of *p*, that is, not *p* will state that “London is not a city” or “It is not true that London is a city”. A particularly important contribution of Khemlani and colleagues is concerned with compound negation [16]. According to the model theory, the negation of a conjunction is harder to represent that the negation of a disjunction because the former requires 3 mental models, while the latter requires only 1 mental model [17]. This prediction can be understood following the formal rules of logic known as DeMorgan´s laws [20,21]. Equations 1 and 2 present the DeMorgan’s laws for any propositions *p* and *q* [1], using the conventional symbols of negation $\neg$, conjunction $\wedge$, disjunction $\vee$ and equivalence $\Leftrightarrow$.

$$\neg(p \wedge q) \Leftrightarrow \neg p \vee \neg q \quad (1)$$

$$\neg(p \vee q) \Leftrightarrow \neg p \wedge \neg q \quad (2)$$

In logic, a proposition is defined as any sentence that can be considered either true or false [3]. If one of these values cannot be clearly attributed, then such sentence cannot be considered as a proposition [1]. An example of the first equivalence in natural language [22,23] is presented in Table 1, which is an actual task that we used in the experiment introduced below.

Table 1. DeMorgan´s law 1 in a natural language experimental task

IT IS NOT TRUE THAT: LONDON IS A CITY AND AFRICA IS A CONTINENT Please select the option (a, b, c, or d) that you think is equivalent to the statement above in capital letters. Two equivalent sentences express the same idea, even when they use different words. a. London is a not a city and Africa is not a continent. b. London is a not a city or Africa is not a continent.* c. If London is a not a city, then Africa is not a continent. d. Either London is not a city, or else Africa is not a continent, but both things cannot be right at the same time.

Note: * normative response according to DeMorgan´s law 1.

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By means of this sentence-equivalence task we found earlier that the negation of a conjunction is harder than the negation of a disjunction [24], that introspection is not an epiphenomenon for these processes [25], that abstraction can be experimentally improved [26], that shallow responses like matching-bias-like responses are the most frequent answers [11], that prior affirmation facilitates the processing of compound negation [27], and that normative responses are a function of representational complexity [5,17]. All these findings were obtained using comparisons of response type. In this study, we aimed to extend such findings by including eye behaviour evidence that uses response time.

Eye movements associated to reasoning processes

The mind-eye hypothesis suggests that some cognitive processes produce specific patters of eye movement [7]. A comprehensive summary of such associations has been extensively reviewed by Rayner in 1978 and 1998 [28,29]. More recently, Oh and colleagues [8] found that eye-tracking provides adequate access to abstract thinking in schizophrenia. Benedek and colleagues [30] found that eye-tracking also generates valuable information about internally and externally directed cognition. McCarthy and colleagues [31] found that culture and context are critical variables that influence eye movement during thinking. In sum, eye-tracking systems are useful tools to generate reliable measures of sentential reasoning in tasks that provide visual information [28,29].

Two working hypotheses can be derived from the current state of knowledge concerned with eye movement during thinking. The first working hypothesis states that gaze dwell times are associated to representational complexity. That is, more complex representations might riquire longer visual inspection and a higher frequency of fixations than simpler representations. In this context, complexity can be understood as the number of mental models required to achieve a sound mental representation [3,5]. The second working hypothesis states that the semantic processing depht is associated to specific patterns of eye movement [29]. That is, more shallow responses might be generated after shorter visual inspection. Similarly, more normative responses might occur after a higher frequency of fixtions. Both working hypotheses are based on previous evidence that relates eye activity to mental processing [28].

Method

We conducted a within-subjects experiment to test four experimental hypotheses derived from our two working hypotheses [32]. We applied an experimental paradigm based on a sentence-equivalence task that was used in previous studies [20,33]. Such task requires the processing of negation for conjunctions and disjunctions according to DeMorgan´s laws (see Equations 1 and 2). Independent variables were defined as the complexity of the reasoning task and the required processing depth. The former was operationalized using DeMorgan´s laws, such that law 1 is more complex than law 2. To negate a conjunction -law 1- requires three mental models and to negate a disjunction -law 2- requires only one mental model [16,17]. We defined two specific gaze behaviour measures as dependent variables: inspection time and fixation. The former can be defined as a time segment measured in milliseconds. During such moment, gaze remains inside a specific area of a computer screen. A fixation can be defined as the permanence of the sight inside a restricted and small area of vision around a particular point -specified by horizontal and vertical coordinates- for more than 150 milliseconds. In other words, a fixation occurs when the eyes stay still while looking at a specific area of the screen during an experiment [29].

Sample

A sample of 34 university students was randomly recruited at the National University of Entre Rios, located at the city of Paraná, Argentina. All the recruited students were undergraduates from Social Sciences careers that exclude logic and mathematics from their study plans. An informative consent form was signed by each subject before taking part in the experiment and the participation remained anonymous. The experimental sessions were conducted individually at the psychology lab located at the same university. 61.8% of the participants (n=21) were female. The total average age was

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22.79 years old (SD=4.22). All the participants had normal vision, that is, none of them used spectacles nor contact lens for visual correction.

Materials and procedure

To evaluate the cognitive processing of compound negation we used a sentence-equivalence task that we applied in several experiments during the last years [5,11,24,25,26,27]. Such task is focused on logical equivalences known as DeMorgan´s laws [20]. According to these laws, the negation of a conjunction is equivalent to a disjunction, and the negation of a disjunction is equivalent to a conjunction [18,19]. Since sentential logic and classic set theory are compatible formalisms, Equations 3 and 4 introduce a mathematical proof of such equivalences for DeMorgan´s law 1 and 2, respectively [26].

$$x \in \overline{P \cap Q} \Leftrightarrow x \notin (P \cap Q) \Leftrightarrow x \notin P \vee x \notin Q \Leftrightarrow x \in \overline{P} \vee x \in \overline{Q} \Leftrightarrow x \in (\overline{P} \cup \overline{Q}) \quad (3)$$

$$x \in \overline{P \cup Q} \Leftrightarrow x \notin (P \cup Q) \Leftrightarrow x \notin P \wedge x \notin Q \Leftrightarrow x \in \overline{P} \wedge x \in \overline{Q} \Leftrightarrow x \in (\overline{P} \cap \overline{Q}) \quad (4)$$

In Equations 3 and 4, x represents any element that belongs to sets like P or Q [18]. The symbols $\cup$ and $\cap$ represent union and intersection of sets, respectively. The symbol $\in$ means that an element belongs to a given set and $\notin$ means that such element does not belong to the given set. The symbol $\Leftrightarrow$ means equivalence between sentences. A line above an expression indicates the complement of the expressed set. These proofs can be applied to natural language [22] since P and Q can be treated as propositions, union can be treated as conjunction and intersection can be related to disjunction [33]. Table 1 shows an example of experimental task associated to Equations 1 -in terms of logic- and 3 -a proof in terms of set theory-.

Each participant was presented with 8 exercises like the one introduced in Table 1. Four exercises applied DeMorgan´s law 1 and four applied DeMorgan´s law 2 (see Equations 1 and 2). The truth value of the atomic propositions was exhaustively combined by pairs, that is, we used true-true (TT), true-false (TF), FT, and FF. Such combination was used for both DeMorgan´s laws to obtain 8 exercises. These combinations replicate previous studies that found no effect for the truth value in compound negation [27]. All the participants completed the full experimental session in less than 10 minutes.

We defined four response options, from which two are particularly important to evaluate our two working hypotheses. We included the normative response according to DeMorgan´s laws, a matching-bias-like response, which preserves the connective given in capital letters (see Table 1), and two additional wrong answers. The matching-bias-like response can be considered as a shallow response [11] because it matches connectives instead of the expected equivalence introduced in Equations 1 and 2.

These exercises were administered individually to each participant using a laptop computer controlled by an eye-tracking system (GazePoint gaze-tracker). We connected a 21 inches LED screen to a 60Hz infrared camera to track eye movement. By means of this setting we measured gaze dwell times and fixations in milliseconds. The participant was instructed to sit in front of a desk. The screen and the camera were over the desk. To give their responses, participants were instructed to use a response device that was connected to the laptop computer. An experimental assistant operated the computer from a desk situated in front of the participant´s desk. The 8 exercises started after the participant completed a training session of 4 exercises. Such training session was introduced to familiarize the participant with the materials, procedure, and apparatus, and to calibrate the eye-tracking system. We used a 9-point calibration process. No participant needed more than one calibration session to provide the system with optimal eye-tracking precision. To obtain specific measures of the response options we defined one area of interest (AOI) for each option (see Table 1, options a, b, c, d). That is, AOIs are geometric squared figures that include the response options of interest. This way, we measured gaze dwell times and fixations for each response option. A partial analysis of eye movement is introduced in Figure 1. AOIs were *post hoc* defined, that is, such definition requires available data for analysis. In Figure 1, for example, the visual analysis suggests that most participants inspected the second response option, which is wrong because DeMorgan´s laws apply only to inclusive disjunction [18,19,20] and this

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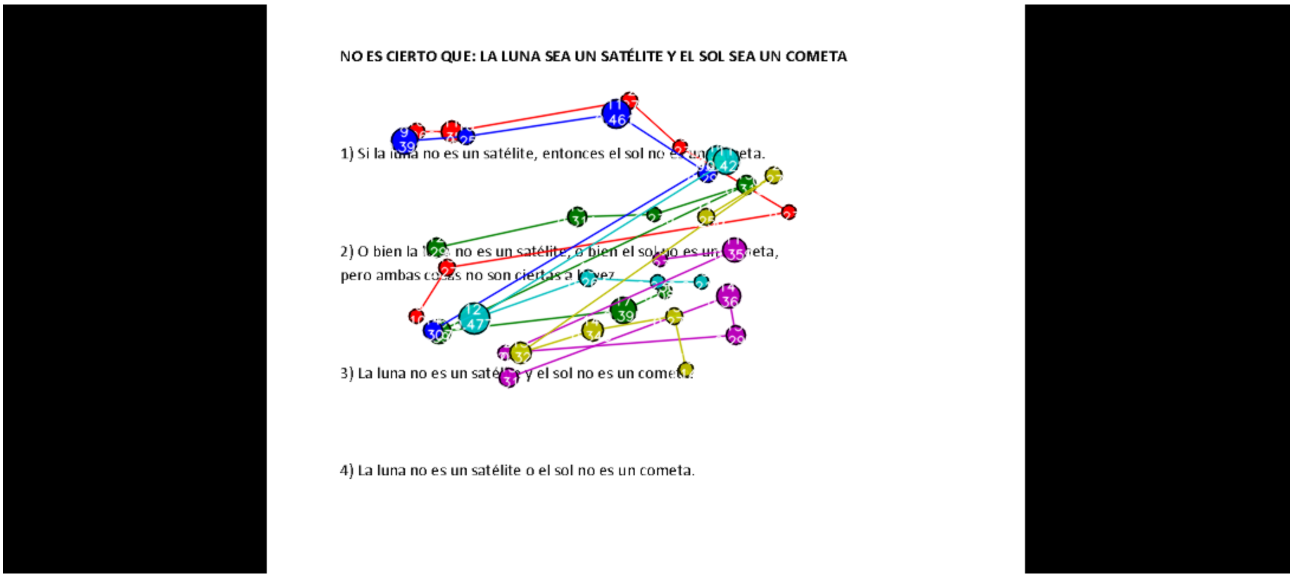
response option uses exclusive disjunction. Sentences in Figure 1 are in Spanish, which is the language of the experimental participants. The prime sentence in capital letters states “IT IS NOT TRUE THAT: THE MOON IS A SATELLITE AND THE SUN IS A COMET”. Response option 1 states “If the moon is not a satellite, then the sun is not a comet”, which is a wrong option [24]. The second option states “The moon is not a satellite, or the sun is not a comet, but both things cannot be true at the same time”, which is also a wrong option [26]. Response option 3 states “The moon is not a satellite and the sun is not a comet”, which is a wrong matching-bias-like response [11]. Option 4 states “The moon is not a satellite, or the sun is not a comet”, which is the normative response [11] according to DeMorgan´s laws (see Equation 3 for a mathematical proof of such equivalence).

Figure 1
Screen Capture of gaze tracking partial analysis for a subset of participants



Note: coloured lines represent eye movements of six participants, one for each colour. Circles represent fixations. Bigger circles represent longer fixations.

Hypotheses
We derived two experimental hypotheses (H1 and H2) from the first working hypothesis, which states that gaze dwell times are associated to representational complexity. Following the same line of reasoning, we derived two further experimental hypotheses (H3 and H4) from the second working hypothesis, which predicts more eye movement for deeper semantic processing when compared to a shallow processing of compound negation. The experimental hypothesis H1 predicts longer inspection times for the negation of a conjunction than for the negation of a disjunction. H2 predicts a higher frequency of fixations for the negation of a conjunction than for the negation of a disjunction. H3 predicts longer inspection times for normative responses than for matching-bias-like responses. H4 predicts a higher frequency of fixations for normative responses than for matching-bias-like responses.
These four experimental hypotheses were derived from the model theory of negation [16,17]. That is, more eye activity should be expected for more complex representation and deeper meaning processing.
Results and discussion

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The evidence resulted consistent with hypotheses H1, H2, H3, and H4. Concerning H1, visual inspection times were significantly longer (t=3.691, p<.001, df=33, Cohen´s d=0.628, medium effect size) for the negation of a conjunction (*Mean*=2347.46ms, *SD*=1035.687) than for the negation of a disjunction (*Mean*=1777ms, *SD*=762.805). Concerning H2, the frequency of fixations resulted significantly higher (t=2.67, p<.01, df=33, Cohen´s d=0.47, about medium effect size) for the negation of a conjunction (*Mean*=4.62 fixations, *SD*=1.78) than for the negation of a disjunction (*Mean*=3.87 fixations, *SD*=1.42). Concerning H3, inspection times resulted significantly longer (t=7.227, p<.001, df=33, Cohen´s d=0.91, large effect size) for normative responses (*Mean*=2908.34ms, *SD*=1058.29) than for matching-bias-like responses (*Mean*=2062.69ms, *SD*=790.511). Concerning H4, the frequency of fixations resulted significantly higher (t=6.216, p<.001, df=33, Cohen´s d=0.88, large effect size) for normative responses (*Mean*=11.2 fixations, *SD*=3.348) than for matching-bias-like responses (*Mean*=8.5 fixations, *SD*=2.765). These results support the model theory of negation and bring problems for alternative accounts focused on logical form because the latter predicts opposite results (in forward thinking) or no difference at all (in backwards thinking). That is the particular case of PSYCOP [13] because such theory distinguishes between forward thinking and backwards thinking. The former moves from premises to a conclusion and the latter moves from a conclusion to its premises.

Discussion

Several decades of research on human thinking has suggested that imagery is a key component of deductive reasoning [4]. Among the main theories proposed to explain how the mind works, the accumulated evidence show that mental representation and inference processed by means of mental models construction is probably correct [3]. In this experiment, we derived two working hypothesis concerned with eye movement during thinking to test the model theory of negation. Particularly, we tested four experimental hypothesis focused on gaze dwell and fixations to compare representational complexity and processing depht. We manipulated complexity using DeMorgan´s laws [18,19,20,21,33] that differentiates between the negation of a conjunction and the negation of a disjunction. The former requires three mental models, while the latter requires only one mental model [1,16,17]. We manipulated processing depth by means of the distinction between normative responses [20], which are difficult and computationally demanding [17], and matching-bias-like responses [10], which are associated to shallow cognitive processing [11].

Our results suggest that the negation of a conjunction is harder to represent than the negation of a disjunction in consistence with previous studies [16,17]. This would happen because the former requires more visual inspection time than the latter in consistence with our experimental hypothesis H1. Furthermore, the former generated a higher frequency of fixations than the latter, in consistence with H2. Taken togehter, H1 and H2 suggest that the representational complexity is a critical aspect of compound negation processing [23]. Several previous experiments yielded similar conclusions [24,25,26,27]. Khemlani and colleages [17] found the same asymmetry between the negation of a conjunction and the negation of a disjunction using a similar selection paradigm and a construction paradigm that requires the processing of DeMorgan´s laws. However, our study originally contributed eye behaviour evidence. Processing depth also resulted critical to understand the cognitive processing of compound negation. Gaze dwell times resulted longer for normative responses than for matching-bias-like responses according to H3. The frequency of fixations resulted higher for normative responses than for matching-bias-like responses in consistence with H4. Taken together, H3 and H4 suggest that processing depth of compound negation is associated to gaze dwell times and to fixations frequency. A deeper semantic processing drives to more active eye movement. Similar results were previously found by Macbeth and colleagues [5] using the same paradigm, but focusing the analysis on response type instead of eye behaviour.

In sum, the present study originally identified eye movement patterns associated to the processing of compound negation that were derived from the model theory of human thinking [3,16,17]. Our results support such theory. A previous study conducted by Orenes and colleagues [6] found that the operation of negation might have an abstract representation. However, such result was

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generated in the context of the visual world paradigm, which is compatible but different than our paradigm. We also measured gaze dwell times as Orenes and colleagues did, but extended the study to include gaze fixations using a sentence-equivalence task.

Since replicability of experimental studies has been intensively discussed lately [34], we tested the consistency of our experiment in comparison with previous experiments focused on the same compound negation task. Several previous studies found that the negation of a conjunction is a harder task than the negation of a disjunction [24]. That is, normative responses to the former are less frequent than normative responses to the latter. Such pattern was previously found by Khemlani and colleagues [16,17], Macbeth and colleagues [5], and Orenes and colleagues [6,7]. We replicated such result in the present study. Normative responses to the negation of a conjunction (*Mean*=0.41, *SD*=0.609) resulted significantly less frequent (sign test, Z=0.002, p<.001, df=33, Cliff´s δ=.505, large effect size) than normative responses to the negation of a disjunction (*Mean*=1.44, *SD*=1.26). This result suggests that our study can be integrated to the current state-of-the-art concerned with the cognitive processing of compound negation.

One limitation of our study is concerned with the lack of pupil dilation measures. This extension is important because a higher pupil dilation has been associated to cognitive effort, which might provide important evidence concerned with representation and inference of compound negation. That is, the negation of a conjunction should produce higher pupil dilation than the negation of a disjunction. Similarly, normative responses should produce a higher pupil dilation than matching-bias-like responses.

Conclusions

Two evidence-based conclusions can be proposed. The first one suggests that the amount of mental representation is associated to gaze dwell times and gaze fixation during compound negation processing. More mental construction seems to generate more visual inspection time and a higher frequency of fixation. The second one suggests that deeper meaning representation requires more gaze dwell time and more fixations than shallower mental representation. These results are consistent with the Mental Models theory of human thinking and inconsistent with logical form accounts of reasoning that hold opposite predictions for the processing of compound negation.

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