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# The Use of Eye-Tracking Technologies in Deductive Reasoning Research

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***Abstract*— Eye-Tracking technologies have strongly increased in deductive reasoning research during the last years. The aim of this paper is to introduce a brief history of its use, to elaborate on some mathematical problems of Eye-Tracking algorithms, to suggest further engineering developments both for hardware and software, to illustrate our proposal with an example of current research on deductive reasoning focused on compound negation, and to discuss the scope and limitations of our contribution. We conclude that Eye-Tracking is a useful tool for Cognitive Science, in general, and for deductive reasoning research, in particular. We also conclude that the future improvement of hardware and software engineering is critical for the potential contribution of this tool to the understanding of human reasoning.**

***Index Terms*— Eye-Tracking, Reasoning Research, Hardware Engineering, Software Engineering**

## I. Introduction

The scientific research in the interdisciplinary field of deductive reasoning has strongly improved during the last two or three decades [1] due to new technologies like functional Magnetic Resonance Imaging or fMRI [2], Event Related Potentials or ERPs [3, 4], Positron Emission Tomography or PET [5], and Eye-Tracking systems [6, 7]. In particular, beyond the important biological advances generated by fMRI, ERPs, and PET, we focus in this study on the psychological advances that became available due to Eye-Tracking systems [8, 9]. In particular, we suggest that the use of new hardware and new software engineering for tracking eye movements provides the opportunity to decompose dependent variables that have often been considered as non-capable of being separated into smaller relevant components. A long tradition in Cognitive Science has derived important conclusions from the analysis of response times or RTs in deductive reasoning tasks performed by human subjects. However, RTs are compound phenomena, that is, the time needed to respond to a deductive reasoning task is additive [10]. The cognitive processes required for visual processing [11], semantic encoding [12], mental models representation [13, 14], inferential processing [15], and counter-examples searching [16], consume a segment of time. RTs are the sum of these time segments for each response that usually is operationally defined as a key press on a response device connected to a computer that controls the visual stimuli presentation [17]. Moreover, the standard deductive reasoning task that presents sentences in a computer screen and records the time elapsed from the presentation of information to the experimental participants' response is only one measure, that is, a single real number expressed in miliseconds. However, the inspection time that the participants dedicated to each sentence or piece of information is not recorded using the standard methods that omit the use of Eye-Tracking technologies.

This paper continues as follows: First, we introduce a brief history of Eye-Tracking technologies, but only from the perspective of deductive reasoning research in Cognitive Science. Second, we highlight some mathematical aspects of Eye-Tracking in the same research field. Third, we mention the aspects that need further engineering development both for hardware and for software and the variables that might be important to include in future Eye-Tracking systems. Fourth, we introduce one example of our current research that has benefited from the use of Eye-Tracking in the study of explicit compound negation [18]. Fifth, we discuss the scope and limitations of our suggestions and, finally, we propose some conclusions.

## II. Brief History of Eye-Tracking in Deductive Reasoning Research

### A. *First Era*

Eye-Tracking systems are not new [8, 9]. They have been used in Cognitive Science for several decades. However, the first apparatuses were invasive, that is, they brought uncomfortable conditions for the experimental participants, humans and non-humans. Nevertheless, the early studies achieved findings that are still valid nowadays. In this era, the researchers discovered the fixation phenomenon, that is, a delay of eyes movements located in a specific point of the visual information that was given. They also found that reading is not linear. We read using progressive and regressive movements, that is, we go forth and back using a rough jump known as *saccadic* movement. Some theory was also developed in this era.

### B. *Second Era*

This period did not develop much theory, nor advanced significantly in hardware engineering. Eye-Tracking systems were contact apparatuses, i.e., invasive. One important finding of this era was concerned with the link between eyes movements and learning. These phenomena were found to be highly correlated.

### C. *Third Era*

First and Second Eras occurred before the Cognitive Revolution [14], that is, they happened before the Second World War and its technological advances. Computer Science was only an elegant mathematical theory [19] before the 1940s [13]. By the contrary, the Third Era benefited from advances in a broad spectrum of sciences and technologies since the 1950s. Computer engineering and software

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engineering started a fast development that brought the possibility of non-invasive Eye-Tracking systems. Therefore, important technological advances were achieved. During the Third Era more relevant theory was clearly developed [20].

### D. Fourth Era

Important developments were conquered during the fourth era. In particular, some computer simulations that predicted positioning of eye gaze using Cartesian coordinates were achieved. Additionally, the inspection time of such positioning appeared as a core variable in Eye-Tracking research. Both of these variables, that is, fixations and inspection time of areas of interest are used nowadays as standard dependent variables. During the fourth era an impressive variety of systems was developed and commercialized. That is, non-invasive hardware that records the exact position of gaze and the duration of such fixation was controlled with more precision. Moreover, a sound articulation of hardware and software began to provide the sequence of fixations in a controlled image presented on a computer screen. That is, the gaze path became a study subject in Eye-Tracking. Additionally, these systems jumped out of the scientific laboratory and started to be used in many applied areas like market research. Eye-Tracking became both, basic and applied research during the fourth era.

In some sense, we are nowadays in the fourth era. During the last years, some important advances have been achieved due to Eye-Tracking in the context of Dual-Process theories of deductive reasoning. In particular, the theory of relevance has suggested that the most selected option in an experimental paradigm known as Wason Selection Task [21, 22, 23] is the most inspected option. This prediction has been extensively corroborated [6, 23, 24] due to Eye-Tracking technologies.

Taken together, these four historical eras have derived in the use of variables like inspection time, gaze fixations, and pupil dilation. The latter has been recently associated to cognitive effort [25] during deductive reasoning in humans.

## III. Mathematics of Eye-Tracking

Eye-Tracking systems employ both deterministic and stochastic mathematics. The former extensively uses matrix algebra and the latter uses data-mining statistical methods. Since these methods have been described with precision in other publications [26], we focus here only on one aspect that brings some problems to the researcher that uses these systems for doing research in the field of deductive reasoning and other similar fields.

The standard method recommended for a specific research depends on the aims of the research, but usually the preferred method in reasoning research is known as the bright-pupil method. This method uses an infrared camera, an infrared light directed to the eyes of the experimental participant, and a triangulation conducted prior to the experiment. This triangulation based on the angle between the bright pupil and a small bright reflection point inside the pupil allows the calculation of the gaze position in the screen of a computer using basic trigonometry. The standard Eye-Tracking infrared cameras can take between 25 and 2000 photos per second. The international standard requires more than 60 Herz for laboratory studies, with preference for systems that provide more than 400 Herz. However, studies conducted outside the laboratory are acceptable with only 25 Herz. This fluctuation affects the accuracy of the system. Faster systems are more expensive. Slower systems are less expensive, but also less reliable and more prone to error. However, the error brought by slow cameras can be corrected using a formula introduced by Andersson, Nyström, and Holmqvist [27]. The use of such formula to transform raw vectors into corrected vectors can reduce the measurement error to less than one millisecond, which is the default standard of quality for 400 Herz cameras. A simple practice that contributes to error reduction is the use of a chinrest that keeps the participant’s head still during the experiment. Our participants usually comment that such procedure does not bother them, nor interferes with their attention. The use of such practice in our experiments reduced dispersion measures like variances and standard deviations, which also brought more power to our statistical tests [28].

## IV. Further Engineering Developments

### A. Areas of Interest

Areas of Interest or AOIs are geometrical figures in two dimensions. That is, areas defined by the user after the experiment. AOIs are usually rectangles around a sentence, but sometimes other figures are needed like circles, ellipses, or irregular areas. More software engineering is needed to easily generate such AOIs.

### B. Inspection Times

Gaze dwell in a specific AOI is measured in miliseconds. However, some experiments require the simultaneous presentation of several AOIs in the same image, e.g. a text of 5 to 10 rows. The problem is that the experimental participants freely move through the image. When the eyes move to a distant AOI, they move across the computer screen and some photos are taken that overestimate the inspection time of an AOI that is in the gaze transition and has no actual interest to the participant. That is AOIs that are simultaneously presented generate an overestimation of inspection time for each other. Although randomization of the position of these AOIs may generate a normal distribution of such error, the overestimation does still exist. Future software engineering shall provide researchers the possibility of restricting the inspection time calculation for a specific AOI that shadows other AOIs. That is, a new method that does not compute for transition AOIs is desirable.

### C. Fixation

Fixation is usually defined as the permanence of the eyes in a very small area during 150 milliseconds or more. However, standard commercial software does not provide the possibility to define this parameter, nor to calculate the frequency of different segments of time. In other words, it is not the same to have 10 fixations of around 300 miliseconds or 10 fixations of around 1000 milliseconds. Such situations need further analysis because a different theoretical interpretation might emerge. A more sophisticated software is needed to perform better analyses.

### D. Computational Demand and Economical Cost

Since Eye-Tracking systems use data-mining methods, the computational demand can be excessive for standard computers. RAM memory might perform in an acceptable manner only with more than 4 GB. One way to solve this problem would be to modularize the software architecture.

That is, the design of the experiment and data collection might be executed using one module. Other module might merge the results obtained by all the participants, and another module might calculate inspection times, fixations, and other visual variables of interest for each AOI. Using this strategy, less RAM memory would be needed to conduct a successful Eye-Tracking experiment. Finally, more open source programs would be helpful for the advancement of the scientific study of deductive reasoning using Eye-Tracking systems.

## V. An Example

The aim of this example is to show that RTs are a weaker dependent variable when compared to separated inspection times for different AOIs presented in the same image. In the same sense, we suggest that fixations provide stronger evidence for experiments concerned with reasoning phenomena. This way, more refined experimental hypotheses can be tested using Eye-Tracking methods. More specific conjectures can be evaluated and stronger evidence can be generated for specific theories.

In an experiment that we have recently conducted, our aim was to test chronometrical predictions derived from the Mental Models Theory or MMT of human thinking [14, 29]. This theory was formulated in the interdisciplinary context of the Cognitive Sciences, which include Psychology, Linguistics, Computer Science, Cybernetics, Philosophy of Mind, and Neuroscience, among others [13]. A recent theory of negation derived from the MMT [30, 31] predicts that the computational processing required for representing different possibilities elicited by the information given modulate the time required for processing deductive inferences. Fixations frequency would also be modulated by the construction of mental models. An important distinction of this theory differentiates between mental models and fully explicit models. The former set of models is a simplified representation of the possibilities compatible with the information given in the experimental task. The latter is an exhaustive set of models that includes all the possibilities. Mental models include only true information whilst fully explicit models include both true and false information for each possibility. The transition from mental models to fully explicit models requires effort, time, and more computational work. To test this working hypothesis, we designed a reasoning task that requires the identification of equivalences for a given negation of a conjunction or given negation of a disjunction. Augustus DeMorgan [18] demonstrated that the negation of a conjunction (law 1) is a disjunction, and the negation of a disjunction (law 2) is a conjunction [32]. According to the MMT, law 1 requires the representation of three mental models and law 2 requires only one mental model. Additionally, the MMT of negation [30] predicts that some logical connectives might motivate the fleshing out of fully explicit mental models. One of such connectives can be the connective for disjunction, which might implicitly invite participants to think using reflection instead of intuition.

### A. Participants

34 undergraduates at the National University of Entre Rios, Argentina, were randomly recruited for the experiment. No reward was given for participation. All the participants took part voluntarily and signed an informed consent before the experiment. They were told that neither deception nor harm would be used in the experiment, and that they could interrupt the experiment whenever they wanted with no consequences. The mean age was 22.79 years old (SD = 4.22). 61.8% were female participants. The experiment was approved by the ethics committee of the University. None of the participants studied logic as part of their respective curricula.

### B. Task example

Tables 1 and 2 show examples for the deductive reasoning task. To perform statistical analyses we defined five AOIs for each item. One AOI was for capital letters only. The other four corresponded to the four response options. For each AOI we computed inspection time and the number of fixations, which were defined as a gaze dwell of more than 150 miliseconds.

**Table 1.** Task example for the negation of a conjunction

| |
|---|
| Instructions: please find the sentence in small letters that is equivalent to the sentence in capital letters. Two sentences are equivalent when they have the same meaning, that is, when they express exactly the same idea. Only one of the four response options is correct according to logic. |
| IT IS NOT THE CASE THAT: LONDON IS A CITY AND AFRICA IS A CONTINENT |
| ☐ a) London is not a city and Africa is not a continent. |
| ☐ b) London is not a city or Africa is not a continent. * |
| ☐ c) If London is not a city, then Africa is not a continent. |
| ☐ d) London is not a city or else Africa is not a continent. |

*Note*. The symbol * shows the correct response according to DeMorgan's law 1.

**Table 2.** Task example for the negation of a disjunction

| |
|---|
| Instructions: please find the sentence in small letters that is equivalent to the sentence in capital letters. Two sentences are equivalent when they have the same meaning, that is, when they express exactly the same idea. Only one of the four response options is correct according to logic. |
| IT IS NOT THE CASE THAT: MESSI IS A SOCCER PLAYER OR FEDERER IS A GOLF PLAYER |
| ☐ a) Messi is not a soccer player and Federer is not a golf player. * |
| ☐ b) Messi is not a soccer player or Federer is not a golf player. |
| ☐ c) If Messi is not a soccer player, then Federer is not a golf player. |
| ☐ d) Messi is not a soccer player or else Federer is not a golf player. |

*Note*. The symbol * shows the correct response according to DeMorgan's law 2.

### C. Design, Materials, and Procedure

A 2 (law factor: DeMorgan's law 1, DeMorgan's law2) single-factor within-subjects design was used in the experiment. We studied response types and response times as dependent variables. The response types were operationally defined by four response options. Each response time was measured in milliseconds using the software PsychoPy [17]. A trial session of 4 items was introduced before the experiment itself. No item from the trial session was included in the experimental session, but the task, response method, instructions and materials' format remained the same. The software PsychoPy was connected to an Eye-Tracking system (GazePoint Gaze Tracker) of 60 Herz, 7 point calibration, and bright-pupil technology, that is, we used an infrared light and an infrared camera.

1 set of 8 exercises was given to all the participants. These exercises were given one at a time. To conduct the experiment, we used a portable computer connected to a 21

inches led screen with full HD resolution. The participant was asked to seat in front of a desk. Over the desk, the screen and a response device were located. The experimenter explained verbally in a few words that the experimental instructions would be given using the screen and that all the responses would be recorded using the response device located in the same desk and a camera. The infrared camera was located under the screen, which was about 65 centimeters away from the chinrest. The participant remained seated during the trial session and the experimental session. The complete sessions took around 10 minutes per participant. Each item took less than 60 seconds in all cases.

### *D. Experimental Hypotheses*

To illustrate the suggestions that we introduced in this paper, we selected from our example two experimental hypotheses. Our aim is to show that these two hypotheses can be properly tested only using Eye-Tracking technology. Hypothesis H1 states that the normative response for law 1 is inspected less time than the normative response for law 2. H2 states that the frequency of fixations for the normative response of law 2 is greater than the frequency of fixations for the normative response for law 1. Both experimental hypotheses are justified using the MMT prediction concerned with the propensity of shifting from a simplified mental model to a more detailed fully explicit model [30, 31], which would be motivated by the disjunctive connective that is negated in law 2.

### *E. Results and Discussion*

Both experimental hypotheses derived from the MMT [1, 30, 31, 33] resulted consistent with the evidence. The AOI defined for the normative response of law 1 (Mean = 1777 milliseconds, SD = 762) was inspected less time ($t = -3.691$, $p = .001$, $df = 33$, Cohen's $d = 1.042$, large effect size) than the AOI defined for the normative response of law 2 (Mean = 2341 milliseconds, SD = 135). This result is consistent with H1. Furthermore, the frequency of fixations for the AOI defined for the normative response of law 1(Mean = 7.742 fixations, SD = 2.846) was smaller ($t = -2.668$, $p = .012$, $df = 33$, Cohen's $d = 0.427$, medium effect size) than the frequency of fixations for the AOI defined for the normative response of law 2 (Mean = 9.275 fixations, SD = 3.558). Taken together, these results suggest that the process of fleshing out fully explicit models has occurred for the logical connective of disjunction, but not for the connective of conjunction. This result cannot be obtained using only RTs for the complete information processing contained in the exercise. Only a decomposition of the response options in different AOIs shall provide appropriate information to test our experimental hypotheses.

One limitation of our study is concerned with the lack of a cognitive effort measure. Eye-Tracking technologies are compatible with such measure, but our system does not provide pupil dilation estimates [25]. The development of such measure as an open source program shall be encouraged in the context of software engineering.

The scope of our findings extends to the use of compound negation in any language. Both natural languages [34] and artificial languages require the use of negation and generate straightforward compound negation theorems. Therefore, our results are ubiquitous, although their applications require further research in specific contexts.

## VI. Conclusion

We conclude that the future development of new hardware engineering and software engineering for Eye-Tracking systems is critical for the advancement of knowledge in deductive reasoning in particular, and in Cognitive Science in general. More specifically, we invite engineers to develop more flexible software based on modules to obtain faster and more efficient systems. For such developments we propose to include pupil dilation measures, a diversity of geometrical figures for the definition of AOIs, and the possibility for the researcher to determine the time required for gaze dwell to define a fixation.

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