Study reveals the cerebral basis of non-verbal deductive reasoning

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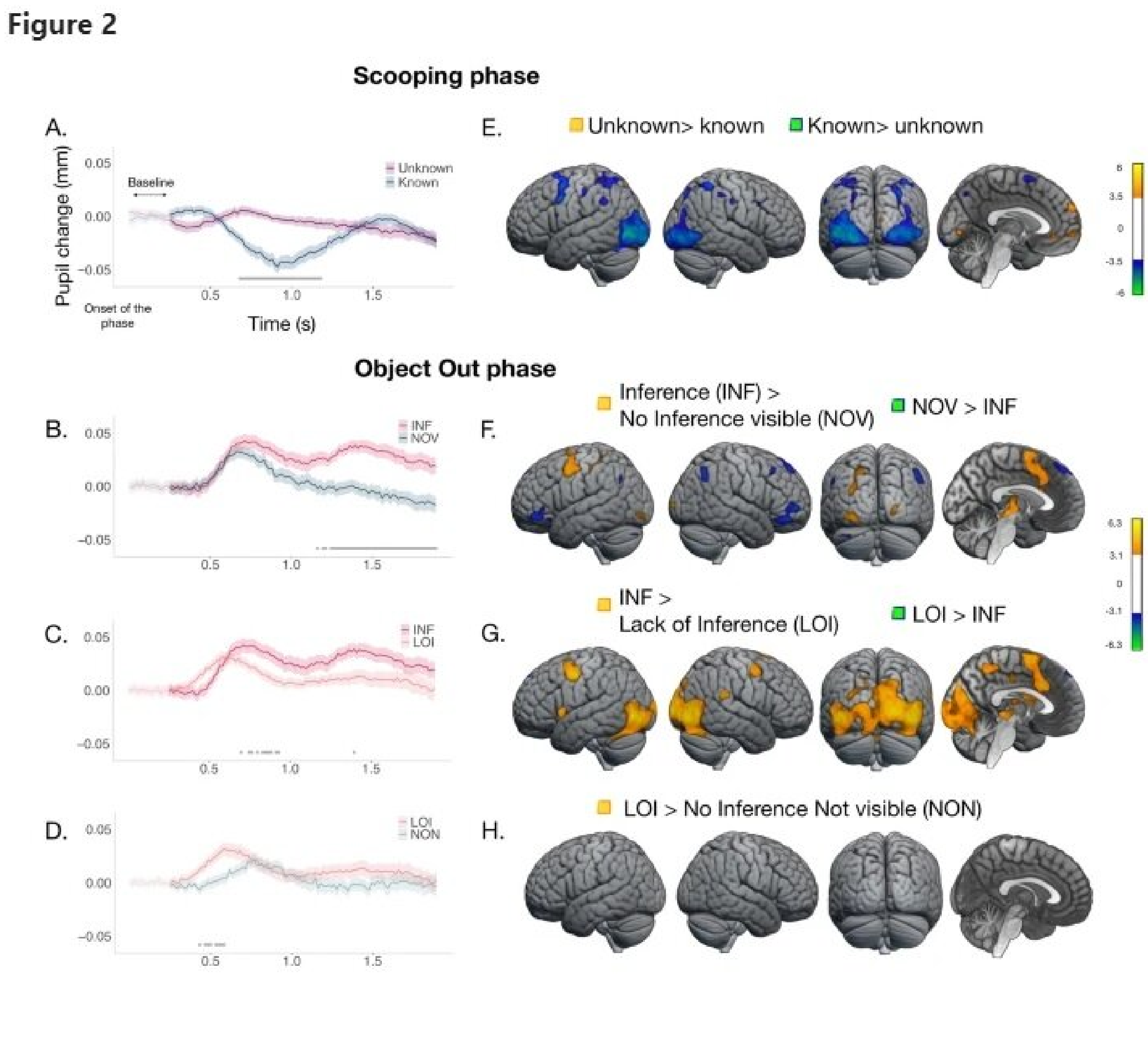

Pupil dilation (Experiment 1) and Brain activations (Experiment 2) during the Scooping and Object Out phases. Credit: *Scientific Reports* (2023). DOI: 10.1038/s41598-023-29307-3

We often express our thoughts in words to communicate ideas, present arguments or make decisions. But what format and structure do these thoughts take in the brain? In the fields of philosophy, psychology and neuroscience, there are still many unknowns surrounding this issue, and it is unclear whether thoughts are represented in the mind by mental models (e.g. images) or by structures and rules similar to those governing language.

To make progress on this matter, researchers from the Center for Brain and Cognition at UPF and other collaborating centers have, for the first time, explored the regions of the brain that activate when only visual scenes that elicit logical inferences are observed.

This study, entitled "Seeing inferences: brain dynamics and oculomotor signatures of non-verbal deduction," was recently published in *Scientific Reports*. Led by Ana Martín (UPF and Ecole Normale Supérieure in Paris), it features a number of international researchers (Christophe Pallier, from the Neurospin Cognitive Neuroimaging Unit, France; and Carlo Reverberi and Aldo Solari, from the University of Milano-Bicocca), together with other researchers from the Center for Brain and Cognition as Luca Bonatti (ICREA-UPF) or Luca Filippin.

The study analyzes the spontaneous logical processes which occur in everyday situations to draw conclusions based on specific information or data. For instance, if we remember buying oranges and apples and see only oranges when we open the fridge, we infer that the apples have already been eaten.

Until now, deductive reasoning has primarily been studied verbally in the field of neuroscience, i.e. researchers have based their analysis of the cerebral responses that occur when making inferences on oral messages or texts. This study, however, takes a novel approach and uses images, i.e. a non-verbal paradigm, to analyze deductive reasoning, making it a pioneering study in the field of neuroscience.

Ana Martín summarizes the study's groundbreaking nature as follows: "For the first time, the basic units of thought are being studied at behavioral level and through brain imagery without recourse to verbal tasks. Observing which brain structures activate when we present visual content compatible with deductive processes may provide clues as to the format in which we represent our thoughts."

Two experiments to examine brain function and pupil dilation during the deduction process

To examine brain function and pupil dilation during deductive processes, the study used a sample comprised of 50 people, with whom two different types of experiments were conducted, both with a common base. In both cases, the participants were shown images in which two objects appear on a stage (e.g. a ball and a snake).

These objects were then covered by an occluder, and one was scooped up by a cup without revealing its identity, meaning that either of the two objects, but not both, could be inside the cup. The participants were required to use the information about the other object to infer which object was hidden in the cup.

Experiments based on simple logic: Disjunctive syllogism (if A is false, B is true)

This methodology employs a simple rule of inference, the so-called disjunctive syllogism, which requires several alternative options (e.g. A or B) and, by a process of elimination, serves to identify which option is true (if not A, then B). This type of paradigm, which is based on visual input, may be used to understand deductive processes at any age, even among babies who have not yet learned to talk.

In fact, the researchers involved in this study already validated this paradigm in a previous study, which was also conducted at UPF, with babies aged 12 to 18 months and adults, and was published in *Science* in 2018.

In the first experiment, brain function was analyzed in the different phases of the deduction process, which is when the different options are represented and the process of deductive elimination takes place. The activation pattern is different in the various phases, indicating that the mental representation associated with the formation of the alternative possibilities is different to the representation associated with the moment the conclusion puts an end to the uncertainty.

Furthermore, in the moment of the inference, this study observed a number of similarities as regards the parts of the brain that activate with respect to studies that used verbal tasks. In both cases, the regions engaged form a prefrontal and parietal network in the left hemisphere. This suggests that, in all forms of reasoning (verbal and non-verbal), these regions play a vital role in logical reasoning.

Martín, however, cautions that this does not mean the brain follows the rules of language when engaging in deductive processes. According to Martín: "It's not that reasoning is linguistic; rather, it is language that is much more dependent on logical processes than generally recognized. The evidence shown here contributes to clarifying the neural mechanisms of elementary logical reasoning in the absence of language."

The pupil dilates more when the image is ambiguous

and triggers a deductive process

In the second experiment, the focus shifted to analyzing the reaction of the pupil, a marker for various cognitive processes in the moment these images are seen.

This second test corroborated that the pupil becomes more dilated in situations in which the individual observes an unknown object, compatible with a disjunction (e.g. it may be the ball or the snake), than with an object the person has already seen. The pupil also dilates more when an inference is performed relative to when it is either not necessary or cannot be performed due to a lack of evidence.

Future challenges: understanding the architecture of thought processes and their development from the earliest stages of life

In short, this pioneering study on deductive reasoning based on moving images serves, through a methodology that uses simple disjunctive syllogisms, to provide further insight into how human thought is represented.

To Martín, these findings are only the tip of the iceberg. She is currently working on other paradigms which aim to provide a better understanding of the architecture of thought processes and their development from the earliest stages of life. Another future challenge involves "adapting and validating this type of material in other species, to determine whether they use logical mechanisms to resolve ambiguous situations that may occur in nature." In fact, behavior compatible with disjunctive elimination has been observed in certain apes and crows.

More information: Ana Martín-Salguero et al, Seeing inferences: brain dynamics and oculomotor signatures of non-verbal deduction, *Scientific Reports* (2023). DOI: 10.1038/s41598-023-29307-3

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