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# The neural development of conditional reasoning in children: Different mechanisms for assessing the logical validity and likelihood of conclusions

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ABSTRACT

Scientific and mathematical thinking relies on the ability to evaluate whether conclusions drawn from conditional (if-then) arguments are logically valid. Yet, the neural development of this ability – termed deductive reasoning – is largely unknown. Here we aimed to identify the neural mechanisms that underlie the emergence of deductive reasoning with conditional rules in children. We further tested whether these mechanisms have their roots in the neural mechanisms involved in judging the likelihood of conclusions. In a functional Magnetic Resonance Imaging (fMRI) scanner, 8- to 13-year-olds were presented with causal conditional problems such as "If a baby is hungry then he will start crying; The baby is crying; Is the baby hungry?". In *Validity* trials, children were asked to indicate whether the conclusion followed out of necessity from the premises. In *Likelihood* trials, they indicated the degree of likelihood of the conclusion. We found that children who made accurate judgments of logical validity (as compared to those who did not) exhibited enhanced activity in left and medial frontal regions. In contrast, differences in likelihood ratings between children were related to differences of activity in right frontal and bilateral parietal regions. There was no overlap between the brain regions underlying validity and likelihood judgments. Therefore, our results suggest that the ability to evaluate the logical validity of conditional arguments emerges from brain mechanisms that qualitatively differ from those involved in evaluating the likelihood of these arguments in children.

## 1. Introduction

Deductive reasoning describes the ability to infer logically valid conclusions from prior information. For example, in the context of conditional rules, deductive reasoning allows one to draw the conclusion "The baby will start crying" from the premises "If a baby is hungry then she will start crying" and "The baby is hungry" (an inference termed *Modus Ponens* or *MP*). Not only is the ability to make such conditional deductions at the heart of scientific and mathematical thinking (Michal and Ruhama, 2008), but impairments in deductive reasoning are observed in children with math learning disability (Morsanyi et al., 2013). Therefore, understanding the neuro-cognitive mechanisms enabling the emergence of deductive reasoning in children is important from theoretical, clinical, and educational perspectives.

Although there is evidence that simple inferences such as Modus Ponens are made relatively early in development (i.e., as early as in kindergarten; Hawkins et al., 1984; Byrnes and Overton, 1986), studies also indicate that young children's deductive behavior is limited. For instance, those children usually fail to detect that the conclusion "The baby is hungry" cannot be logically drawn from the premises "If a baby is hungry then she will start crying" and "The baby starts crying" (an inference termed *Affirmation of the Consequent* or *AC*). This is because there may be other reasons leading to a baby crying, and the conclusion "The baby is hungry" does not follow out of necessity (e.g., the baby may be too cold). Increased ability to reject that AC form is usually observed in young adolescents, at least when premises have a concrete content (Markovits and Vachon, 1990; Barrouillet et al., 2002). Therefore, and although rejecting the AC form remains difficult even for educated adults (Cummins et al., 1991; Markovits and Doyon, 2004), increased ability to reject the AC form is often considered a hallmark of the emergence of deductive reasoning in children.

Over the past decades, studies have found that deductive reasoning

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primarily engages frontal and parietal brain regions in adults (for a review, see Prado et al., 2011). Yet, to our knowledge, only one prior neuroimaging study has investigated deductive reasoning in children (Mathieu et al., 2015), and that study did not differentiate between children who exhibited accurate deductive performance and those who did not. Thus, the brain mechanisms that underlie the emergence of deductive reasoning in children remain unknown. The present functional magnetic resonance imaging (fMRI) study had two main goals. The first one was to identify the brain regions in which activity differs between children who reject the AC form and those who do not, thereby shedding light on the brain regions that underlie the emergence of deductive reasoning with conditional rules in children. We presented children between 8 and 13 with conditional problems of the AC form in a fMRI scanner (note that this relatively wide age range was chosen so that a relatively large variability in deductive responses could be observed). We asked them to indicate whether conclusions followed out of necessity from the premises (i.e., *Validity* trials, see Table 1). Activity during the evaluation of the AC form was systematically compared to a baseline in which children evaluated conclusions of more simple problems of the MP form, which children older than 8 should uniformly endorse (Markovits et al., 1996; Janveau-Brennan and Markovits, 1999). This was done to ensure that reasoning activity during evaluation of the AC form was isolated from activity related to reading a conditional rule and activity associated with selecting between two responses (both of these components were similar in AC and MP forms, see Monti et al., 2007 for a discussion of baseline issues in neuroimaging studies of reasoning). Activity during the evaluation of the AC form (compared to the MP form) was then related to rate of acceptance of the AC form across subjects, thereby identifying the brain regions underlying the emergence of deductive reasoning with conditional rules (i.e., the brain regions in which activity increased as rate of acceptance decreased).

The second goal of our study was to shed light on a debate between *one-process* and *two-process* theories about the nature of the mechanisms allowing for the emergence of deductive reasoning in children. On the one hand, one-process theories assume that deductive reasoning is an extension of the type of inductive reasoning used in everyday life, i.e., when one infers conclusions that are more or less likely given prior information and knowledge (Heit and Rotello, 2010; Rotello and Heit, 2009). For example, proponents of the influential Mental Model theory of deductive reasoning – which assumes that reasoners construct spatial mental representations of the premises when drawing deductive inferences – have argued that the same type of mechanisms underlie deductive and inductive reasoning (Johnson-Laird, 1994). More recently, researchers have proposed Bayesian accounts of deductive reasoning that assume that judgments of logical validity are determined by judgments of likelihood (Oaksford et al., 2000; Oberauer, 2006). For instance, consider the problem "If a baby is hungry then she will start crying; The baby starts crying; Is the baby hungry?". Bayesian theories posit that reasoners may intuitively calculate the likelihood of a baby being hungry given that she starts crying. This likelihood is relatively high, so the conclusion that the baby is hungry might be drawn by some individuals when faced with the premise "The baby starts crying". However, likelihood estimates vary between individuals and will change with experience (Evans and Over, 2013; Evans et al., 2015; Oaksford and Chater, 2001). Thus, Bayesian theories can explain why rejection rates of the AC form varies between individuals and typically increase over development: Because older children have a broader knowledge base than younger children, a given premise (e.g., "The baby starts crying") is more likely to evoke multiple associated causes in older than younger children (e.g., "The baby is hungry, "The baby is cold" etc.). This will lower the certainty of the conclusion. Overall, then, Bayesian theories assume that judgments of likelihood may translate into likelihood of rejection of a deductive argument, either directly (e.g., a conclusion associated with a probability of 60% might be accepted about 60% of the time; Liu and Song, 2003), or indirectly using an internal threshold (i.e., a conclusion may only be accepted if the associated probability is above a certain threshold; Oberauer, 2006). In sum, one-process theories do not see any major qualitative difference between evaluating the logical validity and the likelihood of a conclusion.

On the other hand, two-process theories assume that the mechanisms supporting judgments of logical validity are different from those underlying judgments of likelihood. For instance, the Mental Logic theory posits that deductive reasoning relies on formal rules of inference that are specific to logic and therefore cannot account for inductive reasoning (Braine and O'Brien, 1998). A developmental variant of the Mental Model theory proposed by Markovits and Barrouillet (2001) also makes a distinction between evaluating the logical validity and the likelihood of conclusions in children. Specifically, this model emphasizes that deductive reasoning relies on the retrieval of relevant knowledge stored in long-term memory. For instance, in the problem mentioned earlier (i.e., "If a baby is hungry then she will start crying; The baby starts crying; Is the baby hungry?"), reasoners may search for an alternate cause leading to a baby crying (i.e., other than the baby being hungry). If at least one alternative is found (e.g., a baby may cry because she is too cold), the conclusion that the baby is hungry will not be made. Thus, unlike Bayesian theories, this theory does not posit that reasoners intuitively compute likelihoods when assessing conclusions. Rather, they may search for counterexamples and a conclusion will be rejected if at least one counterexample is found. Clearly, the representation and maintenance of such counterexamples relies on working-memory resources (Markovits and Doyon, 2004). Therefore, a developmental increase in working-memory capacity may be at the heart of the increased ability to reject the AC form with age (Markovits and Barrouillet, 2001; Barrouillet and Lecas, 1999; De Neys and Everaerts, 2008). Finally, the idea that judgments of logical validity and likelihood are different is broadly consistent with dual-system theories of reasoning, which posit that two types of cognitive processing underlie human reasoning (Evans and Stanovich, 2013). The first type (often referred to as 'heuristic' or 'intuitive') is fast, unconscious, and autonomous. The second type of processing (often referred to as 'analytical' or 'deliberate') is slow, conscious, and controlled. It has been proposed that judgments of likelihood, which rely on associative information and similarity, are more likely to involve heuristic than analytic processing. In contrast, judgments of logical validity, which require deliberative and accurate reasoning, are more likely to rely on the analytic than the heuristic processing (Heit and Rotello, 2010; Rotello and Heit, 2009; Heit, 2014). In sum, two-process theories posit that there is a difference between evaluating the logical validity and the likelihood of a conclusion, either because these processes rely on entirely separate mechanisms or on a different mixture of heuristic and analytic processing.

In the present study, in addition to identifying the brain regions underlying the emergence of deductive reasoning with conditional rules, we aimed to shed some light on the debate between one-process and two-process theories. That is, we tested whether the brain regions that underlie the emergence of deductive reasoning overlap with the brain circuits associated with judging the likelihood of conclusions. This was done by presenting children – in a second part of the experiment – with conditional problems of the AC form and asking them to indicate on a scale the likelihood of the conclusion (i.e., *Likelihood* trials) (Markovits and Thompson, 2008). Activity during the evaluation of the AC form

**Table 1**
Examples of AC and MP forms in *Validity* and *Likelihood* trials for the rule "If a baby is hungry then she will start crying".

| Logical form | Premise | Question |
|---|---|---|
| *Validity* trial | | |
| MP | A baby is hungry | Is it certain that she will start crying? |
| AC | A baby starts crying | Is it certain that she is hungry? |
| *Likelihood* trial | | |
| MP | A baby is hungry | How sure it is that she will start crying? |
| AC | A baby starts crying | How sure it is that she is hungry? |

Notes: MP: Modus Ponens, AC: Affirmation of the Consequent.