Title: Precursors of logical reasoning in preverbal human infants

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RUNNING HEAD: Precursors of logical reasoning

ONE SENTENCE SUMMARY:

Behavioral markers of spontaneous inferences reveal nonverbal logical reasoning in infants and adults.

ABSTRACT:

Infants possess remarkable capacities to entertain hypotheses about complex events and to modify them rationally when faced with inconsistent evidence. These capacities suggest that infants can use elementary logical representations to frame and prune hypotheses. By presenting scenes containing ambiguities about the identity of an object, here we show that 12-and 19-month-old infants look longer at outcomes that are inconsistent with a logical inference necessary to resolve such ambiguities. At the moment of a potential deduction infants' pupils dilated, and their eyes moved towards the ambiguous object when inferences could be computed, in contrast to transparent scenes not requiring inferences to identify the object. These oculomotor markers resembled those of adults inspecting similar scenes, suggesting that intuitive and stable logical structures involved in the interpretation of dynamic scenes may be part of the fabric of the human mind.

MAIN TEXT:

Fifty years ago, Piaget argued that logic in the mind is the culmination of a long developmental process, extending into adolescence. Forty years ago Fodor answered that if learning implies testing hypotheses, then learners must possess the representational resources to formulate them, including logical primitives: rule-like combinatorial concepts embedded in a compositional system of representation, or a language of thought (*1*).

After four decades, we still lack insights into the nature and development of the logical representations, if any, structuring infants' thinking and problem-solving. Partly, this profound lack of knowledge stems from the widespread belief that infant cognition relies on independent modules, functioning early and efficiently, but not supported or connected by general reasoning (*2*). Partly, it stems from the assumption that while logical representations are involved in processing language, and hence are present in organisms that master a natural language, it is difficult, perhaps impossible (*3*), to identify them in nonverbal organisms (*4*). Indeed, acquiring language does improve cognition, perhaps also by creating novel logical representations (*5*). However, none of these considerations weakens the real force of Fodor's argument, although its premises need to be reappraised. While infants possess learning mechanisms which do not require hypotheses (e.g., bottom-up tracking of statistical regularities; *6*), flexible and productive hypothesis testing does begin in infancy, with a vengeance. Infants can generate hypotheses about future uncertain events (*7*), flexibly adapting them to novel, albeit subtle, elements of a situation (*8, 9*). They measure the evidence in their support (*10*), and test alternative hypotheses when violations occur (*11, 12*). Such abilities extend far beyond precompiled mechanisms for domain-specific responses, displaying a high degree of rationality in several domains. One prominent account of them depicts infants as precocious Bayesian reasoners. However, most Bayesian theories require a logical scaffolding to formulate, test and modify hypotheses (*8, 13–15*). Thus, characterizing the basic logical representations available to preverbal infants for formulating hypotheses remains fundamental to understand the very nature of knowledge acquisition (*16*).

Here we begin investigating the developmental precursors of such scaffolding, looking for behavioral correlates of one simple logical representation and rule: disjunction (Either A or B) and disjunctive syllogism (Not A; therefore B). While elementary, this schema grounds one crucial hypothesis-testing strategy: Sherlock Holmes-like case-by-case analysis of different possibilities, excluding alternatives until the culprit is found. Attempts to find clear evidence of disjunctive syllogism in nonhuman animals are so far inconclusive (*4, 17*). A related reasoning pattern has been studied in toddlers' and preschoolers' word learning strategies (*18, 19*), but it is unknown whether it is within the conceptual repertoire of preverbal infants. Here, we first investigate whether infants can frame disjunctive hypotheses and make inferences by logically eliminating alternatives, testing their reactions to outcomes that violate conclusions of this deductive process. Then, we identify markers of inferential activity online by examining oculomotor responses during inference making. Finally, we explore stability across development, by comparing the oculomotor responses of infants, toddlers and adults passively looking at non-verbal scenes potentially involving logical inferences.

We studied 12- and 19-month-old infants, two ages at the onset of speech production and language learning, but prior to the development of extensive language knowledge. We presented infants with scenes injected with ambiguity about the identity of an object, which could be resolved *via* disjunctive syllogism. In Experiments 1-2, two objects different in shape, texture, color and category, but with identical top parts (say, an umbrella and a doll), enter a virtual theater (Fig. 1; fig. S1). An occluder hides them, and a cup scoops one of them from behind it, leaving only the top part visible. Thus, infants cannot know the identity of the scooped object and may establish a disjunctive representation. Then, the occluder moves downwards, revealing one object -- say, the umbrella. We call this moment the *Potential Deduction phase:* here infants have evidence to disambiguate the identity of the scooped object by disjunctive syllogism. Finally, in the *Outcome phase,* the umbrella leaves the stage and the cup reveals the second object. Half of the times, the revealed object is consistent with the conclusion suggested by the logical inference (it is the doll), whereas in the other half it is inconsistent (it is the umbrella). We recorded looking time during the Outcome phase in a Violation of Expectation (VOE) paradigm. Both 12- and 19-month-olds looked longer at the inconsistent outcome, suggesting that they may have derived the identity of the object in the cup *via* logical inference and were surprised when such conclusion was violated [Experiment 1, 19-month-olds, N=24: $M_{Consistent}$ = 7.7 s, $M_{Inconsistent}$ = 10.5 s; $F(1, 23) = 5.79$, $P = 0.025$; Experiment 2, 12-month-olds, N=24 : $M_{Consistent}$ = 6.2 s, $M_{Inconsistent}$ = 7.6 s; $F(1, 23) = 5.19$, $P = 0.032$); Repeated Measures ANOVAs].

In Experiments 1-2, in an inconsistent outcome an object appears twice successively: the occluder lowers revealing the umbrella, the umbrella exits the stage, and then the cup reveals an umbrella again (Fig. 1A, *vi-2*). Instead, in a consistent outcome two different objects appear successively: after the umbrella exits, the cup reveals the doll. Thus, infants may have reacted, not to a logical inconsistency, but to the surface aspects of the final sequence, when the same object appeared twice in succession (Fig. 1A, *vi-1*). In Experiments 3-4, the logical status of the final object sequence reverses (Fig. 2A). Movies are identical to those of Experiments 1-2 until the Potential Deduction phase. There, the occluder never lowers; the umbrella exits from its side, remaining visible for about 1.5s and returns behind it. In the Outcome phase, the cup never reveals its content. Instead, another object exits the occluder: sometimes the umbrella again, and sometimes the doll (50% each; Fig. 2A,*vi*). The former outcome is consistent with the logical inference; however, unlike Experiments 1-2, one single object is seen twice in succession. The latter outcome is inconsistent, but two different objects are seen once in succession. If infants respond to the surface aspects of the final sequence, they should disregard the logical consistency of the outcome and look longer when the single object appears twice, as in Experiments 1-2. If, instead, their behavior is guided by a logical inference, they should look longer when the outcome is inconsistent with it even if the final sequence reverses that of Experiments 1-2. Indeed, both 19 and 12-month-olds looked longer at the inconsistent outcome (Fig. 2C), suggesting that they reacted to the logical gist of a scene [Experiment 3, 19-month-olds, N=24: $M_{Consistent}$ = 4.9 s, $M_{Inconsistent}$ = 6.2 s; $F(1, 23) = 8.5$, $P = 0.008$; Experiment 4, 12-month-olds, N=24: $M_{Consistent}$ = 4.2 s, $M_{Inconsistent}$ = 6.1 s; $F(1,23) = 11$, $P = 0.003$; Repeated Measures ANOVAs]. These results also control for other non-logical explanations, such as an object's magical disappearance in the inconsistent outcome of Experiments 1-2 (no such disappearance occurred in Experiments 3-4), or its greater featural variability in Experiments 3-4 (reversed in Experiments 1-2).

VOE only measures a response *post hoc,* after a conclusion has been reached (*20*). Adults reasoning with language make disjunctive inferences as early as they possess the relevant evidence (*21, 22*). The data reported so far do not characterize the unfolding of an inference in the infant mind. To explore this, we analyzed oculomotor responses during the Potential Deduction phase. We created novel scenes identical to Experiments 3-4 in the Potential Deduction and Outcome phases, but requiring no inference to identify the object in the cup (Experiments 5-6; Fig. 2B). We obtained this by showing the cup scooping one object in full view before occlusion. Thus, unlike Experiments 3-4, in Experiments 5-6 infants already know which object is in the cup before the Potential Deduction phase. As expected at these ages (*23*), infants looked longer at an outcome inconsistent with the identity of the (known) object in the cup [Experiment 5, 19-month-olds, N=24: $M_{Consistent}$ = 3.8 s, $M_{Inconsistent}$ = 8.3 s; $F(1, 23) = 26.1$, $P = 0.0001$; Experiment 6, 12-month-olds, N=24: $M_{Consistent}$ = 4.9 s, $M_{Inconsistent}$ = 6.2 s; $F(1, 23) = 4.9$, $P = 0.037$]. But our focus here is the temporal course of oculomotor responses during the Potential Deduction phase, which we expected to be modulated by the need for an inference. Indeed, cluster-based permutation tests (*24, 25*) revealed that at several points during the Potential Deduction phase the infants' pupils dilated more when the scene licensed an inference than when it did not, suggesting increased cognitive activity possibly due to inference making. By the end of this phase, infants also displaced their eyes towards the cup more markedly [Fig. 3B-C; SOM] and switched their focus from the visible object to the cup in more trials [$M_{Inference}$ = 71%, $M_{No\_Inference}$ = 50%; $F(1, 88) = 10.4$, $P = 0.002$; fig. S2; SOM] when a deduction was needed than when it was not. Remarkably, only when the Potential Deduction phase afforded an inference did higher pupil dilation and visible object-to-cup shifts contribute to predict success at identifying inconsistencies in the later Outcome phase. No such predicting relation occurred absent the need for an inference [fig. S3; SOM]. The fact that this relation occurred only when an inference may be involved suggests that oculomotor markers in the Potential Deduction phase are not simply due to memory of past event structures, but are tied to some kind of mental inference about the identity of the object in the cup, drawn online when infants acquire the disambiguating evidence.

Thus, these oculomotor markers suggest that preverbal infants efficiently deploy logical procedures to process the components of an unfolding scene. To assess developmental stability, we inspected adults' oculomotor responses during the same Potential Deduction phase. Adults (Experiment 7; N=30) saw 96 scenes patterned upon those of Experiments 1-6. Like infants, during the Potential Deduction phase adults' pupils dilated more, and their eyes tended to look more towards the cup, when the scene licensed an inference. Again, this occurred regardless of its physical realization. Indeed, adults and infants differed only in the speed of such markers, but not qualitatively [Fig.

3D; figs. S4-S5; SOM].

Our data document the early presence of primitive logical abilities. Without instructions or tasks, infants spontaneously reason logically while a scene unfolds. Specific behavioral markers can be used to study the precise temporal course of their reasoning process. Because such markers already appear at ages when language development has barely begun, our data suggest that precursors of logical reasoning are independent of language acquisition. Their stability across ages and spontaneous deployment suggest that some form of elementary logical reasoning may be a primitive property of the logical circuitry in the human brain (*26*). Explaining our data without invoking deductive inferences has a cost. Bayesian iterative models, which evaluate the most likely of the alternatives first and cycle through them when the first choice is discarded, could mimic deductive syllogism without assuming a logical inference in the Potential Deduction phase. However, they require that infants represent the space of alternatives (which is equivalent to implementing a disjunctive representation), assign ordered priors to the alternatives, and assess alternative evaluations iteratively. A logical inference require less assumptions. Thus, while compatible with Bayesian reasoning, the hypothesis that infants perform a logical inference in the Potential Deduction phase is a more parsimonious explanation of the current results.

On the face of the stability we document, children begin mastering a verbally expressed disjunction quite late in development (*17*). A dissociation between spontaneous inferential abilities in nonverbal contexts and their explicit verbal counterparts need not imply lack of a concept. Instead, it indicates that mapping the spontaneous logical structures of thought onto their verbal counterparts is an extremely intricate process. A deceivingly simple word such as 'or' has a very complex semantics (*27*). Unambiguous evidence for its meaning is difficult to come by, a difficulty that affects the acquisition of even simpler abstract words (*28*). Thus, a consequence of our research is that much work is still needed to understand how the proper alignment between language and thought occurs.

This is the first empirical evidence relevant to the old, yet still fundamental questions debated between Fodor and Piaget. Logical representations that are crucial components of infants' natural hypothesis-testing attitude are available when infants start projecting and testing hypotheses about the world. Such representations may consist of non-linguistic, but fully language-like structures, or may piggyback on sophisticated object representations that can track object identities in ambiguous situations. Although further research is needed to clarify their nature, our data suggest that intuitive and stable logical structures involved in the interpretation of dynamic scenes may be essential part of the fabric of the mind. This does not imply that *all* logical reasoning is spontaneous or innate, just as spontaneous and innate elementary numerical abilities do not imply that *all* mathematical knowledge is innate. Reasoning occurs in many different forms and at many different levels of our mental processes and the gulf separating infant thinking from adult explicit logical reasoning remains large. However, the development of reasoning abilities builds on a natural logical foundation, whose profile we are beginning to uncover.

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This paper is dedicated to the memory of J.A.F.

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Materials and Methods

Figs. S1 to S6

Table S1

Movies S1 to S9

References (*29*)

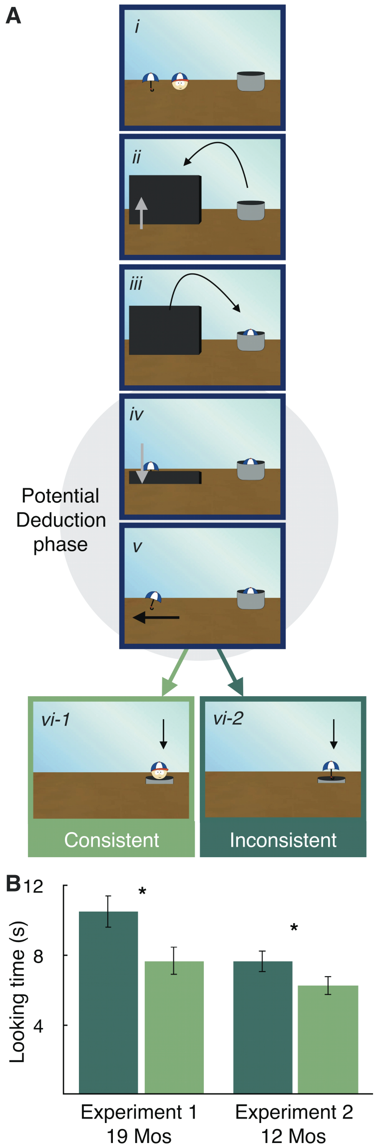
Figure Captions

Fig. 1. Infants look longer to outcomes inconsistent with a logical deduction. (**A**) (**i**) Two objects with an identical upper part enter the theater. (**ii**) An occluder hides them and a cup scoops one from behind, leaving only its top part visible (*umbrella OR doll?*). (**iii**) The occluder lowers (**iv-v**), allowing to infer its identity (*not umbrella, therefore doll*). (**vi**) The cup reveals its content, which is either consistent (*doll*) or inconsistent (*umbrella*) with the inference. (**B**) Mean looking time (SEM) at the outcomes (s). Both 19- and 12-month-olds looked longer at the inconsistent outcome. $^{*}P < 0.05$.

Fig. 2. Infants' logical reasoning does not depend on how the scene is physically realized. (**A**) (**i-iii**) Inference condition: The identity of the object in the cup cannot be determined prior to the Potential Deduction phase. **(B) (i-iii)** No-Inference condition: the cup scoops the object in full view, so its identity is known. (A and B) **(iv-v)** Potential Deduction phase (common): Only in the Inference condition is a deduction needed to determine the cup content. Note the very different physical realization of this phase compared to that of Experiments 1-2. (A and B) **(vi1-vi2)** Outcome phases (common): An object exits the occluder, yielding a consistent/inconsistent outcome. (**C**) Mean looking time (SEM) at the outcomes (s). Both 12- and 19-month-olds looked longer at the Inconsistent outcome. $^{*}P < 0.05$; $^{**}P < 0.01$; $^{***}P < 0.001$.

Fig. 3. Pupil dilation and eye position during the Potential Deduction phase may signal online logical inferences. (**A**) Subcomponents of the Potential Deduction phase, time-adjusted to participants' ages (color-marked in indigo shades). (***iv-a***) An object exits the occluder. (***iv-b***) It stops by the cup containing a second object whose identity is either known (No-Inference condition) or ambiguous (Inference condition). For participants in the Inference condition, this is the first moment when evidence is available to disambiguate the cup content. (***iv-c***) The visible object returns behind the

occluder. (***iv-d***) The object remains hidden inside the cup, onstage. (**B**-**D**) Temporal course of Pupil dilation changes (mm) from baseline and Mean-*x* gaze positions (px) for (B) 12-month-olds, (E) 19-month-olds and (D) adults, in the Inference (blue) or No-inference condition (red). Data are plotted starting when the mean *x* coordinates of the two conditions converged on the object emerging from the occluder. Error bars are SEM for infants and 95% within-participants confidence intervals for adults. Yellow dots indicate regions of differences in the two conditions (cluster-based permutation tests; SOM). During the Potential Deduction phase, at all ages, participants who had to perform a logical inference to identify the cup content had pupils more dilated and gazed more towards the cup.


A
i
ii
iii
iv
Potential
Deduction
phase
v
vi-1
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Experiment 1
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Experiment 2
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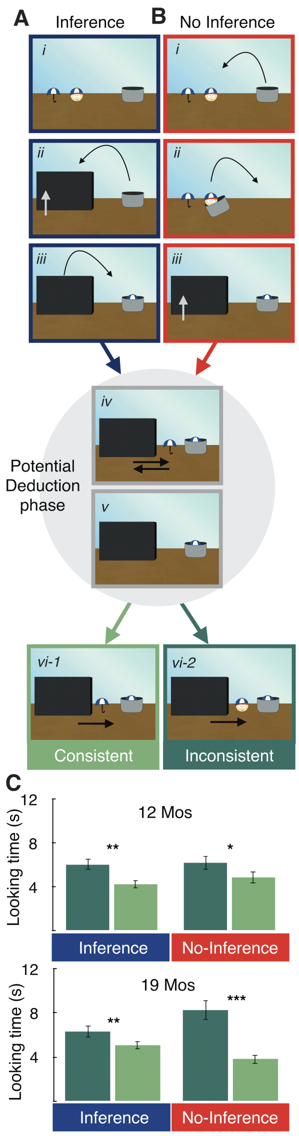
A
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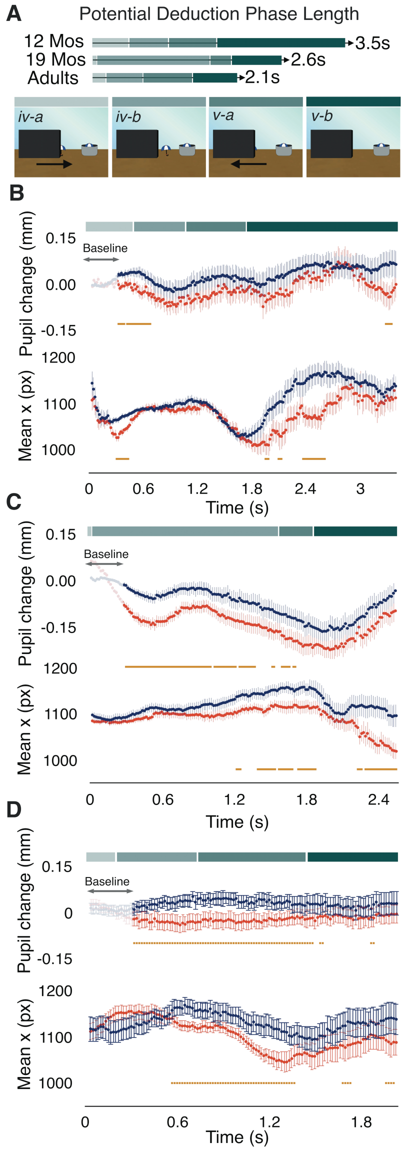
A
Potential Deduction Phase Length
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3.5s
19 Mos
2.6s
Adults
2.1s
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iv-b
v-a
v-b
B
Pupil change (mm)
0.15
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Mean x (px)
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