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## 4 **Curiosity as a metacognitive feeling**

5

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7

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13

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16

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## 22Abstract (228 words)

23Curious information-seeking is known to be a key driver of learning, but  
24characterizing this important psychological phenomenon remains a challenge. In  
25this article, we argue that this requires qualifying the relationships between  
26metacognition and curiosity. The idea that curiosity is a metacognitive  
27competence has been resisted: many researchers have assumed both that young  
28children and non-human animals can be genuinely curious, and that  
29metacognition requires conceptual and culturally situated resources that are  
30unavailable to young children and non-human animals. We suggest that this  
31resistance is unwarranted given accumulating evidence that metacognition can  
32be deployed procedurally, and defend the view that curiosity is a metacognitive  
33feeling. Our metacognitive view singles out two monitoring steps as a triggering  
34condition for curiosity: evaluating one's own informational needs, and  
35predicting the likelihood that explorations of the proximate environment afford  
36sizeable information gains. We review empirical evidence and computational  
37models of curiosity, and show that they fit well with this metacognitive account,  
38while on the contrary, they remain difficult to explain by a competing account  
39according to which curiosity is a basic attitude of questioning. Finally, we  
40propose a new way to construe the relationships between curiosity and the  
41human-specific communicative practice of questioning, discuss the issue of how  
42children may learn to express their curiosity through interactions with others,

43and conclude by briefly exploring the implications of our proposal for  
44educational practices.

45**MAIN TEXT (11499 words)**

46

47

48**1) Introduction**

49

50Curious information-seeking has long been identified as a key driver of learning  
51(Baldwin & Moses, 1996; Berlyne, 1978; Bruner, 1961; Dember & Earl, 1957),  
52and exciting empirical research has largely confirmed this assumption by  
53gathering data in human adults, children and infants, as well as in non-human  
54primates (Begus & Southgate, 2018; Gottlieb & Oudeyer, 2018; Gruber,  
55Gelman, & Ranganath, 2014; Kang et al., 2009; Kidd & Hayden, 2015). The  
56status of curiosity, however, remains hotly debated. There is at present no  
57consensus about how to define and operationalize this important psychological  
58phenomenon, nor about its emergence across ontogeny and phylogeny (Begus  
59& Southgate, 2018; Carruthers, 2018; Kidd & Hayden, 2015).

60

61This article proposes that defining curiosity requires clarifying its relationship  
62with metacognition, broadly defined as the ability to evaluate the quality of  
63one's own informational states, and the efficiency of one's own learning  
64attempts, in order to regulate subsequent cognitive activities and behavior. Many  
65researchers have resisted the idea that curiosity is fundamentally a metacognitive  
66competence, because they have assumed both that non-human animals and

67young children can be genuinely curious - since they engage in information  
68seeking even when this does not lead to immediately consumable rewards  
69(Bazhydai & Westermann, 2021; Gottlieb & Oudeyer, 2018; Kang et al., 2009;  
70Kidd & Hayden, 2015) - and that metacognition requires conceptual and  
71culturally situated resources that are unavailable to young children and non-  
72human animals (Bazhydai & Harris, 2021; Begus & Southgate, 2018;  
73Carruthers, 2018a,b; Perner, 2012).

74

75Here, we argue that this resistance is not warranted: a large body of research  
76suggests instead that metacognition does not reduce to its conceptual, meta-  
77representational forms, and that preverbal children and some nonhuman animals  
78possess rudimentary metacognitive resources (Goupil & Kouider, 2019; Proust,  
792012, 2019; Shea et al., 2014). In our view, intrinsic curiosity must involve  
80minimal forms of metacognitive monitoring and regulation allowing agents to  
81identify and satisfy their informational needs, which we refer to as "core" or  
82"procedural" metacognition. Our suggestion is thus that, from early on in  
83development, and across animal taxa, engaging in curious information seeking  
84is, fundamentally, a metacognitive competence.

85

86First, we will present a basic definition of curiosity and a few important  
87functional distinctions. We will then introduce two competing theoretical  
88accounts that both attempt to characterize the semantic structure of curiosity,

89and its link with metacognition. According to a first account, curiosity is a basic  
90affective attitude of questioning (BQA account, Carruthers, 2018<sub>a,b</sub>). According to  
91our proposal, curiosity is a metacognitive feeling whose function is to motivate  
92cognitive agents to adaptively fill their informational gaps (MF account). We  
93then discuss relevant empirical and theoretical arguments, and conclude that a  
94metacognitive account is to be preferred, both on theoretical and empirical  
95grounds. Finally, we discuss the relationship between questioning and curiosity  
96in cross-cultural contexts and over development, and briefly explore the  
97implications of our proposal for educational practices.

98

99

## 100) **What is curiosity?**

101

### 102**.a.) Basic definition and functional distinctions**

103

104Curiosity is the mental property that is pretheoretically used to explain why  
105people actively seek information. Why does Ann ask a question about a given  
106event? Because she is curious: she wants to ascertain whether an event  
107happened, and/or to learn more about where, when and why it happened.  
108Curiosity then, is a mental state whose function is to trigger information search,  
109and that is extinguished when information is obtained (Berlyne, 1962; Kidd &  
110Hayden, 2015; Loewenstein, 1994).

111

112 Curiosity leads to exploring (Berlyne, 1966), but it is worth noting that not  
113all explorations are driven by curiosity. Explorations are behaviors whereby  
114agents search their environment. They are ubiquitous across the animal  
115kingdom, and can be driven by different motives. Utility-driven (or  
116instrumental) explorations have a non-cognitive goal, such as foraging for food  
117or shelter. Curiosity-driven explorations, by contrast, occur when agents seek  
118information for its own sake. In experimental contexts, curiosity is hypothesized  
119to lead to exploratory behaviors when animals are satiated and safe (Kidd &  
120Hayden, 2015; Oudeyer & Smith, 2016).

121

122This distinction between utility-driven and curiosity-driven explorations is  
123blurred whenever instrumental explorations incidentally lead to information  
124gains. Imagine that you just moved in a foreign country. In the morning, you try  
125to find a coffee shop. During this utility-driven exploration, you may notice  
126events that surprise you (i.e., that differ from the expectations you formed on the  
127basis of your prior knowledge). For example, a surprising traditional outfit could  
128pique your curiosity, and lead you to want to know more about it (e.g. its name,  
129its social meaning). Here, your desire for coffee incidentally triggered unrelated  
130curiosity-driven information search.

131



132The two types of exploration have a distinctive selective history and hence,  
133different primary functions (Millikan, 1989). It is likely that utility-based  
134exploration was selected first, to allow organisms to decide whether to exploit  
135identified resources, or to sacrifice current gains with the prospect of better  
136future rewards. A further adaptation then allowed organisms to explore their  
137environment to gain information in the absence of a current instrumental need,  
138leading to curiosity-driven explorations. Their primary function is to enrich the  
139model used for predicting future events, in order to reduce subjective uncertainty  
140(Koechlin, 2014). In this view, curiosity is part of the complex and multifaceted  
141set of abilities involved in computing the trade-off between exploring and  
142exploiting (Schwartenbeck et al., 2019).

143

144Our example above highlights surprise as a *precursor* to curiosity (Vogl,  
145Pekrun, Murayama, & Loderer, 2019), and we discuss this possibility further in  
146*Appendix 1*. Surprise is triggered when an unexpected event occurs, that is, an  
147event that contradicts the agent's prior beliefs. The resulting prediction error can  
148then enhance the agents' attention, leading them to revise their priors in an effort  
149to minimize future prediction errors (Hohwy, 2012; Sim & Xu, 2019). Surprise  
150and curiosity are often equated with one another (Kidd & Hayden, 2015;  
151Schwartenbeck et al., 2019), but they are functionally distinct: surprise can lead  
152to curiosity – as in our example above (see also Ligneul, Mermillod, &  
153Morisseau, 2018) – but it can also trigger sequential utility-driven explorations:

154if an animal is surprised not to find food in a predicted location A, it may search  
155for it in other locations out of sheer utility, rather than curiosity.

156In summary, surprise-based sequential explorations stem from experiencing  
157local prediction errors, i.e., a divergence between internal predictions and  
158observed outcomes (Egner, Monti, & Summerfield, 2010). Their primary  
159function is to allow agents to notice unpredicted changes, and to locally adjust to  
160them. Curiosity-based explorations stem from detecting an informational need,  
161and are terminated once this informational need is satiated. They can be  
162triggered by surprise, when surprise leads agents to recognize that they have an  
163informational need, but can also be triggered by other mechanisms. Curiosity  
164primarily depends on an organism's ability to become sensitive to its  
165informational needs, and the aim of a theoretical account of curiosity should  
166thus be to try and characterize how these informational needs are detected. This,  
167in our view, requires clarifying the links between curiosity and metacognition.

168

## 169**2.b.) Curiosity and metacognition: two views.**

170

171Two main views have been proposed to qualify the relationship between  
172curiosity and metacognition. A first view is that curiosity is is a *basic*,  
173*prelinguistic affective attitude of questioning*, that is triggered automatically  
174when a cognitive activity fails to generate the expected outcome. A second view  
175is that curiosity is a *metacognitive feeling* that stems from evaluating one's own

176informational needs, and the likelihood that exploring will lead to information  
177gains in a given context.

178

### 179**2.b.i Curiosity as a basic questioning attitude (BQA).**

180

181This view proposes that curiosity is akin to the process of questioning, and is  
182one of its evolutionary and developmental preconditions. Building on a proposal  
183by epistemologist Dennis Whitcomb (Whitcomb, 2010), Peter Carruthers (2018)  
184observes that the content of a curious attitude (e.g., the question “*where are my*  
185*keys?*”) specifies the set of propositional attitudes that would count as an answer  
186(e.g., “*the keys are in the drawer/in my bag/on the table*”). Extinguishing  
187curiosity requires selecting a correct answer in this set of alternatives, leading to  
188the formation of a novel belief (e.g., “*I believe the keys are in the drawer*”). In  
189this view, curious states are desire-like attitudes, because they have strong  
190motivational and affective dimensions, but they differ from first-order desires  
191because the agent seeks knowledge rather than consumption.

192

193A key aspect of this view is that curiosity does not presuppose metarepresenting  
194one's own knowledge, or lack thereof. For instance, the questioning attitude  
195“*where are the keys?*” requires that the agent has a concept of “*keys*”, but not  
196necessarily a concept of “*knowing*”. As such, basic questioning attitudes (BQAs  
197thereafter) can be available to nonhuman animals and pre-linguistic children.

198The defining feature of this affective state is that it has an interrogative content  
199(expressed in words: “where is X?”): it is a kind of attitude. In contrast with  
200metarepresentations, however, its content does not consist in embedded  
201propositions such as "X wants to *know whether it rains*". Accordingly, it only  
202requires mastering the first-order concepts that apply to the emotion-triggering  
203situation (related, for example to predation, foraging, mating). Thus, note that in  
204this view, curiosity does not require metacognition – equated by the author with  
205the ability to form metarepresentations (Carruthers, 2016; Perner, 2012).

206

207In summary, according to this account, only first-order concepts are needed to  
208generate basic questioning attitudes, and to grasp and memorize answers to it.  
209These affective attitudes of questioning are proposed to arise automatically  
210when a cognitive activity (e.g., remembering) fails to generate the expected  
211outcome (e.g., recovering a piece of information from memory).

212

### 213**bii. Curiosity as a metacognitive feeling (MF)**

214On an alternative view, curiosity is a specific kind of metacognitive feeling that  
215arises when agents evaluate that they have an informational need in a specific  
216context. On this view, curiosity depends on two types of assessment, bearing  
217respectively on the agents' own lack of knowledge and on the potential learning  
218gains afforded by their proximate environment.

219

220This proposal is informed by dual-process accounts of metacognition (see the  
221*Appendix 2* for details, and a defense of these accounts against the  
222metarepresentational views mentioned above). Although they differ in their  
223details, dual-process accounts propose that metacognition does not boil down to  
224the ability to form metarepresentations, and does not need to rely on concepts -  
225such as “knowing” or “being certain” (Koriat & Levy-Sadot, 1999; Proust, 2012;  
226Shea et al., 2014). Instead, they propose that metacognition encompasses all of  
227the mental processes whereby agents internally evaluate the reliability of their  
228cognitive activities (deciding, remembering, learning...), and use such  
229information (e.g., a confidence, fluency or error signals) to regulate subsequent  
230cognitive activities. These evaluative processes give rise to metacognitive  
231feelings, which in turn initiate exploratory or corrective epistemic behaviors. On  
232this view, metacognition can thus be deployed non-conceptually – in the form of  
233“subjective experiences with a distinct embodied phenomenal quality and a  
234formal object” of varying valence and intensity (Proust, 2015) - in order to  
235evaluate informational needs or achievements. On the other hand, concept-based  
236processes broaden the scope of metacognitive control by integrating  
237considerations about tasks, individual competences, social environment etc. (A.  
238Koriat & Levy-Sadot, 1999).

239

240This article proposes that curiosity is a special type of metacognitive feeling.  
241Many affective responses, such as the experience of pleasure in relaxing, or of

242painful exertion, primarily stem from monitoring bodily states. Metacognitive  
 243feelings, however, are affective responses that stem from monitoring the success  
 244or failure of one's own cognitive actions (identifying, discriminating,  
 245recognizing, remembering, learning, etc.). Their generic function is to predict  
 246feasibility or success in various types of cognitive tasks (in perception, memory,  
 247or reasoning...) based on different temporal segments of the cognitive activity  
 248(predictive, current, retrospective). As shown in Table 1, each type of  
 249metacognitive feeling motivates a specific kind of control: launching a cognitive  
 250task, revising it, accepting or rejecting its outcome. Curiosity belongs to the  
 251predictive kind of metacognitive feelings: one that is concerned with identifying  
 252informational needs and strategically planning explorations to satiate those  
 253needs.

254

Goal-related predictive feelings	Process-related evaluative feelings	Result-related evaluative feelings
Feelings of curiosity	Feelings of error	Feeling of being right/wrong
Feelings of familiarity	Feelings of incomprehension	Feeling that one learned ("judgement of learning")
Feelings of knowing	Feelings of incoherence	Eureka feeling
Feelings of prospective confidence	Feelings of interest/boredom	Feelings of retrospective confidence
Tip-of-the tongue	Feelings of confusion	

255Table 1. Taxonomy of metacognitive feelings based on activity segments being assessed. This  
 256taxonomy manifests the similarity between feelings of curiosity, feelings of knowing (Koriat, 1995),  
 257feelings of familiarity (where a face, for example, motivates searching who that person is (Whittlesea,  
 258& Williams, 2001) and tip-of-the tongue-phenomena (Frazier et al, 2021). They all reflect a tension

259that motivates further search; their positive valence expresses the promise of closing an informational  
260gap.

261

262**2.c. Divergences between the basic questioning attitudes and the**  
263**metacognitive accounts.**

264Do the two views really differ ? At first sight, characterizing curiosity as a basic  
265affective attitude might seem congruent with proposing that curiosity is a  
266metacognitive feeling, and both BQAs and MFs are claimed to be present in  
267nonhumans and in prelinguistic children. The two views differ, however, on two  
268important issues. Their first divergence bears on the *definition* of metacognition.  
269The second divergence relates to *functional differences* between basic  
270questioning attitudes and metacognitive feelings.

271

272*2.c.i) Divergence 1: Two ways of defining metacognition.*

273

274The BQA account is part of wider explanatory framework in which  
275metacognition is defined as cognition about one's cognition, and equated with  
276the ability to form metarepresentations (i.e., propositional attitudes about  
277propositional attitudes such as “*I believe that [I remember P]*”). As a  
278consequence, only conceptual forms of self-attribution of knowledge or  
279uncertainty are worth the name of metacognition (Carruthers, 2016, 2018;  
280Perner, 2012, but see Carruthers, 2020). On the MF view informed by dual-  
281processing accounts of metacognition, in contrast, feelings generated by the

282evaluation of cognitive actions also qualify as metacognitive. A detailed defense  
283of the dual-processing view of metacognition is provided in *Appendix 2*. We  
284argue that the notion of metacognitive feeling is a necessary intermediary  
285explanatory notion to guide research on curiosity, because it can explain how  
286curiosity can be deployed non-conceptually while still possessing subject-  
287specific and context-specific features. Hence, metacognitive feelings can explain  
288the transition from first-order evaluations to concept-based metarepresentations.  
289This is described in greater details in section 3).

290

291*2.c.ii) Divergence 2: Affective attitude versus metacognitive feelings.*

292One might still argue that, aside from the definitional issue, BQA as presented in  
293Carruthers (2018) has much in common with a view emphasizing the role of  
294metacognitive feelings. Both accounts involve a prelinguistic, affective mental  
295construct whose function is to drive intrinsic exploratory behavior in  
296nonhumans, young and adult humans. There are three important functional  
297differences between the two accounts, however, which lead to very different  
298implications and predictions.

299

300First, the two constructs *are based on different underlying mechanisms*. BQA  
301draws on an analogy with semantic constructs such as beliefs and desires. Just as  
302having a belief is the (non-metacognitive) causal precondition for making an  
303assertion, having a desire-like attitude to know something is the (non-



304metacognitive) causal precondition for deploying information-seeking. As an  
305attitude, BQA needs to have a (first-order) concept-based propositional content:  
306"Why is this person wearing this strange outfit"?

307

308In contrast, dual-process theorists of curiosity do not endorse the view that  
309curiosity needs to involve propositional contents. The basic ontology of MF  
310rather includes predictions and evaluations – i.e., comparators, a calibration  
311process, and the associative cues that can enhance or influence predictions. No  
312restriction, then, is imposed on the representational input to curiosity. Curiosity  
313can stem from a mere feeling of surprise triggered by an unexpected stimulus  
314(Ligneul et al., 2018; Vogl et al., 2019), or by a feeling of familiarity  
315(Whittlesea & Williams, 2001), a tip of the tongue phenomenon (Frazier,  
316Schwartz, & Metcalfe, 2021), etc. Graded MFs primarily stem from consciously  
317experiencing these evaluative processes and their outputs, rather than forming  
318propositional attitudes involving first- and second-order concepts.

319

320A second difference consists in the semantic relations between curiosity and its  
321triggering condition. On the basic questioning view, being curious about the  
322name of the capital of New Zealand is an affective attitude toward a desired  
323piece of information, conceptually represented through first-order concepts (“the  
324capital of New Zealand is...”). Yet, BQA does not say much about how a  
325specific trigger generates an adaptive exploration. It only proposes that a BQA is

326automatically generated when a cognitive action (e.g., a remembering attempt)  
327fails. Instead of this all-or-none mechanism, MF proposes instead that curiosity,  
328like any other (metacognitive) feeling, primarily derives from experiencing  
329analog evaluative processes, and as such, has a *graded valence and intensity*.  
330This graded nature allows organisms to select a specific cognitive focus, and to  
331modulate the intensity of their exploring behaviors, as a function of their prior  
332knowledge, and of the informational gain afforded by the specific context they  
333are in.

334

335A third difference relates to the issue of whether curiosity is a basic or a  
336complex ability. BQA argues that curiosity is basic, which means that it is  
337irreducible to further drives and semantic contents. By contrast, the  
338metacognitive account proposes that curiosity stems from an open set of  
339evaluative processes that assess subjective uncertainty, detect prediction errors,  
340and motivate exploration as a function of its expected positive or negative value  
341(Gottlieb, Oudeyer, Lopes, & Baranes, 2013; Litman, 2008). As we describe in  
342greater details below, such combined sensitivity to context and prior knowledge  
343is most clearly manifested in the U-shape of curiosity: curiosity requires a  
344minimal amount of knowledge to arise, and it stops when the information need  
345is satisfied (Kang et al., 2009).

346

347

### 3483) Focusing on curiosity as a metacognitive feeling.

349

350In the preceding section, we introduced two main theories of the semantic  
351structure of curiosity. They diverge on three crucial issues : 1) the constitutive  
352role of *first-order concepts* versus *evaluative processes*; 2) the *interrogative*,  
353*all-or-none* versus the *evaluative, graded* structure of curiosity; 3) the *basic*  
354versus *complex* (i.e., subject- and context-sensitive) nature of curiosity. In this  
355section, the properties of curiosity are analysed along these three axes, on the  
356basis of developmental, experimental and computational evidence. Curiosity is  
357shown to include two key monitoring steps: 1) an evaluation of the internally  
358available information, and 2) an evaluation of the potential information gains  
359afforded by a specific context. The evidence that curiosity is supported by  
360graded, subject- and context- sensitive evaluative processes is compatible with  
361the idea that curiosity is a metacognitive feeling rather than a basic questioning  
362attitude.

363

364*First step: monitoring prior states of knowledge*

365Berlyne long ago hypothesized that specific forms of curiosity are meant to  
366reduce the *cognitive conflicts* associated with subjective uncertainty (Berlyne,  
3671961). In a similar spirit, it was later proposed that curiosity is elicited by  
368perceived *informational gaps* (Loewenstein, 1994). This theory predicts that  
369agents will be curious when they encounter a situation in which several

370alternative interpretations are compatible with the current situation, given  
371agents' prior beliefs. Agents then compare their confidence estimates for each  
372alternative. Below a given confidence threshold, a drive to collect additional  
373information arises (Golman & Loewenstein, 2018; Loewenstein, 1994).

374

375This model is consistent with the key finding that self-reported curiosity  
376depends on agents' evaluations of their prior knowledge. "Feelings-of-knowing"  
377and "tip-of-the-tongue" experiences (i.e., metacognitive feelings that occur  
378when one is unable to recover an information from memory, but still feels that  
379one knows it) are associated with greater attempts at recovering a memory,  
380greater curiosity, and greater information seeking than "I don't know" or "I  
381know" states (Litman, 2005; Loewenstein, 1994; Maril, Simons, Weaver, &  
382Schacter, 2005; Metcalfe, Schwartz, & Bloom, 2017). In situations where  
383information gain is guaranteed - because exploring leads to encountering stimuli  
384that are easy to process - human adults typically seek information when they  
385have low confidence (Desender, Boldt, & Yeung, 2018). For instance, in a  
386recent study, when an algorithm was trained to classify high versus low  
387confidence responses from electroencephalographic data, it could also  
388accurately predict whether participants would engage in information seeking or  
389not (Desender, Murphy, Boldt, Verguts, & Yeung, 2019).

390

391Low confidence already predicts information-seeking early on in development

392(Coughlin, Hembacher, Lyons, & Ghetti, 2014; Goupil & Kouider, 2019;  
393Lapidow, Killeen, & Walker, 2021). For instance, in a perceptual task, 3- to 5-  
394year-old children preferentially seek additional information – instead of  
395responding by themselves – in conditions in which they also report low  
396confidence on a picture-based scale (Coughlin et al., 2014). In the language  
397domain, 4-year-olds’ curiosity about word meanings varies as a function of their  
398confidence (Jimenez, 2018; Jimenez, Sun, & Saylor, 2018). In the memory  
399domain, even 20-month-olds seek help when they forgot the location of a toy, to  
400avoid recollection errors (Goupil, Romand-Monnier, & Kouider, 2016).

401

402In summary, from early on in development, empirical evidence indicates that  
403information seeking is supported by metacognitive monitoring processes that  
404allow agents to evaluate their informational needs. Evaluating prior knowledge  
405is thus a key factor driving curiosity, but it is only sufficient to guide curiosity in  
406environments where explorations tend to lead to information gain. In an  
407uncertain world, however, explorations can be fruitless. Hence, curiosity should  
408also depend on the expected information gain afforded by a specific context for  
409a specific learner.

410

411*Second step: trade-offs between prior knowledge and sources of knowledge.*

412It has long been known that even infants orient their attention as a function of  
413how familiar a stimulus is to them (Fantz, 1964; Hunter, Ross, & Ames, 1982),

414and more recent research has shown more specifically that infants tailor their  
415attention as a function of how predictable and informative stimuli are (Kidd,  
416Piantadosi, & Aslin, 2012; Poli, Serino, Mars, & Hunnius, 2020). Infants tend to  
417look away from events that are either too easy to process (because they are  
418highly predictable) or too difficult to process (because they are highly  
419unpredictable). This attentional strategy characterizes infants' individual  
420exploratory behavior toward visual as well as auditory stimuli (Kidd et al., 2012;  
421Kidd, Piantadosi, & Aslin, 2014). Beyond stimulus predictability, a recent study  
422found that the way infants pay attention to a visual display also depends on how  
423much information can be gained from a specific observation, given all past  
424observations of the display (Poli et al., 2020). Thus, from early on in  
425development, attentional allocation depends on evaluations of potential  
426information gains afforded by a specific context.

427

428Combined with the monitoring step described above, these evaluative  
429mechanisms can allow learners to adjust their explorations as a function both of  
430the informational need they identified, and of the potential gain their proximate  
431environment affords. As mentioned above, where exploration is guaranteed to  
432result in information gains because it leads to discovering stimuli that are easy to  
433process, low-confidence is linearly associated with information-seeking  
434(Coughlin et al., 2014; Desender et al., 2018). By contrast, contextual variations  
435in the likelihood that exploring will provide information gains leads to a U-

436shape function: curiosity is maximal when participants have middle-range levels  
437of confidence (Kang et al., 2009).

438

439This U-shape function can be accounted for by complexity theory (Dember &  
440Earl, 1957; Kidd & Hayden, 2015), which proposes that curiosity varies with a  
441system's ability to absorb new information. The best learning target is neither  
442overly simple (already encoded into memory), nor “too disparate from existing  
443representations already encoded into memory” (Kidd et al., 2012). Complexity  
444theory matches Lev Vygostky’s notion of a zone of proximal development.  
445Instructional guidance, Vygostky observed, is most efficient when learning  
446goals are neither already met, nor too distant from the student’s existing  
447acquisitions (Metcalf, Schwartz, & Eich, 2020; Vygotsky, 1978).

448

449*Progress learning theory*. It has been objected to complexity theory that the  
450notion of an "intermediate challenge" remains to be operationalized (Oudeyer,  
451Gottlieb, & Lopes, 2016). Furthermore, there are many intermediate complexity  
452stimuli that do not trigger explorations, especially in changing environments  
453(Schmidhuber, 2010). A dynamic version of complexity theory, progress  
454learning theory (PLT), initially developed in developmental robotics, claims that  
455the brain, as a predictive machine, "*is intrinsically motivated to pursue activities*  
456*in which predictions are improving*" (Luciw, Kompella, Kazerounian, &  
457Schmidhuber, 2013; Oudeyer et al., 2016). Curiosity, on this view, is an intrinsic

458motivation whose function is to identify "niches of learning progress".  
459Specialized predictive heuristics influence the intrinsic motivation to engage or  
460disengage from an activity (Luciw et al., 2013). On the one hand, monitoring  
461one's prediction error rates offers a way to assess task difficulty, which motivates  
462exploring mildly unfamiliar topics (in agreement with complexity theory). On the  
463other hand, monitoring one's progress rate of learning (i.e. the temporal derivative  
464of performance) dictates when to engage in, persist in, or disengage from  
465learning when exploring would likely not lead to any information gain (Ten,  
466Kaushik, Oudeyer, & Gottlieb, 2021). These two components map onto the two  
467monitoring steps singled out in the MF model.

468

469A complementary Bayesian approach specifies how the exploration-exploitation  
470trade-off varies as a function of the types of uncertainty encountered in a given  
471context, and evaluations of prior knowledge (Friston et al., 2017; Schwartenbeck  
472et al., 2019). When reliable information is available, exploration should target  
473either events to-be-predicted ("hidden state exploration"), or the causal,  
474parametric structure of the model itself ("model parameter exploration"). When  
475it is not, they should proceed randomly.

476

477*Curiosity as a rational behavior:* A rational account of curiosity has also been  
478defended in order to distinguish the subjective and objective forms of  
479informational uncertainty at play in curiosity. It proposes that *the value of*



480*knowledge* depends on the causal structure of the environment, and that the  
481function of curiosity is to rationally seek information that is maximally useful  
482for the agent in a given context (Dubey & Griffiths, 2020). This can explain that  
483people are more curious about novel facts in changing environments where past  
484events are less likely to recur in the future. It can also explain why the  
485relationship between uncertainty and curiosity varies as a function of how  
486instrumental it is to gather information in a given situation: when a decision  
487must be made, and accuracy is important, it is rational to seek information when  
488uncertainty is maximal. By contrast, if information can be collected without  
489direct instrumental pressure, it can be rational to orient to intermediate levels of  
490uncertainty that afford sizeable informational gains at lower processing costs.  
491On this view too, the feelings associated with novelty, learning rate, complexity  
492and other factors might all influence curiosity. The function of curiosity, again,  
493consists in tracking stimuli likely to maximize the overall value of knowledge  
494acquisition in a given type of environment. Curiosity is thus the set of  
495mechanisms that approximates the rational behavior of seeking stimuli allowing  
496agents to maximize their ability to make appropriate responses in the future.

497

498Although successfully tested through computational simulations, developmental  
499robotics, and adult game decisions, these theories await further evidence from  
500developmental studies. As reviewed above, we have evidence that information-  
501seeking relates to confidence (Coughlin et al., 2014; Goupil et al., 2016), and

502that attention allocation reflects the potential information gain afforded by a  
503specific context (Kidd & Hayden, 2015; Poli et al., 2020) from early childhood.  
504But when do children start integrating both kinds of evaluations to engage in  
505curious-based explorations? This remains unknown. We examine this specific  
506question in further details in *Appendix 1*.

507

508*Valence and intensity.*

509Another key aspect of curiosity - compatible with the idea that it constitutes a  
510metacognitive feeling - is that it varies in valence and intensity. As observed by  
511Berlyne (1978) and Loewenstein (1994), experiencing a conflict or detecting an  
512informational gap may generate an aversive feeling, which in turn motivates the  
513exploratory behavior predicted to suppress the unpleasant current feeling. Yet,  
514exploration is an approach behavior because it predicts a positive experience of  
515interest and the resolution of one's own perceived ignorance. Consistent with  
516this, neural systems typically involved in reward anticipation also show  
517increased activity for information anticipation during curiosity or curiosity relief  
518(Gruber et al., 2014; Kang et al., 2009; Lau, Ozono, Kuratomi, Komiya, &  
519Murayama, 2020; Ligneul et al., 2018).

520

521The hybrid, "interest-deprivation" model (Litman, 2009) thus hypothesizes that  
522curiosity is a trade-off between opposed motivations: a *positive motivation* for  
523learning – interest – and a *negative emotion* generated by uncertainty and the

524prospect of a possible learning failure. The respective weights of these affects  
525reflect variations in learning goals. The trade-off might include additional  
526motivations. The anticipated valence of the *information to be gained* has also  
527been claimed to bias learning goals, and hence, curiosity about them. People  
528seem to be less curious to know about predictably bad news than they are about  
529good news (Gottlieb et al., 2013, but see FitzGibbon, Lau, & Murayama, 2020).  
530This motivational articulation is compatible with the proposal that metacognitive  
531feelings integrate predictive cues when monitoring a cognitive action from goal  
532selection to action completion (see Table 1 above).

533

534In summary, the evidence discussed in this section shows that, in line with the  
535MF view, metacognitive monitoring is a key triggering condition of curiosity.  
536Empirical and computational work indeed shows that curiosity expresses a  
537trade-off between various motivations, each endowed with their own valence  
538and intensity. This recognition speaks in favor of taking curiosity to be a  
539metacognitive feeling that reflect subjective and strategic evaluations of  
540informational needs, rather than constituting a basic affective attitude that is  
541triggered automatically in an all-or-none fashion.

542

543

544**4) Curiosity and questioning**

545

546 This being said, granting that in the BQA view, curiosity is a basic form of  
547 questioning, the MF view needs to clarify the relations between curiosity and the  
548 specifically human questioning behavior. The two theoretical accounts make  
549 radically different proposal regarding this aspect. In the BQA view, questioning  
550 and curiosity are essentially one and the same attitude. By contrast, in the MF  
551 view defended here, curiosity is a metacognitive feeling that can occur in the  
552 absence of any questioning ability. What additional functional steps, then, are  
553 involved when children start expressing their curiosity through questions?  
554 Before describing the relevant empirical data, the notion of questioning needs to  
555 be carefully examined. We will first analyze questioning as a communicational  
556 practice involving an inquisitive action, verbal or non-verbal, from a sender S to  
557 a receiver R, and clarify its semantic structure. We will then discuss the  
558 possibility that early, non-verbal forms of questioning express curiosity, and  
559 examine empirical evidence related to the question of whether and how  
560 questioning is scaffolded by interactions with caregivers.

561

562 ***4.a.) The semantic structure of questioning.***

563

564 Questioning is often produced to reduce S's subjective uncertainty, or to test R's  
565 knowledge about a given subject matter, but it can also be used to provoke  
566 specific non-epistemic responses from R. Typically, in English, the function of  
567 the speech act "where is the salt?" is not to know where the salt is, but to request

568the salt: it expresses a desire rather than curiosity. In Quichuan as in most other  
569languages, questions can be used to emphasize doubt to serve rhetorical  
570purposes rather than request information (Nuckolls & Swanson, 2018). Thus, S  
571may question R because *she wants to know something* from R (curiosity-driven,  
572epistemic questions), because she wants to deny the relevance of a potential  
573objection (pragmatic goal-driven, rhetorical questions), or more simply, because  
574*she wants something* from R (utility-driven questions)<sup>1</sup>.

575

576Furthermore, articulating epistemic questions (verbally or nonverbally) requires  
577mastering the semantic structure for interrogative contents (Roberts, 2012). A  
578question not only has a *focus*, such as a new object in the environment; it also  
579represents a *topic*: a range of options to be narrowed down concerning the focus  
580(for example, how to name this object, or how to play with it?). Adequately  
581answering a question, then, requires identifying its focus along with the set of  
582relevant topical alternatives – or "contrastive topics" - that the questioner has in  
583mind.

584

585

586***4.b.) From curious explorations to verbal questioning.***

587

---

<sup>1</sup>) Of note, this heterogeneity of question use is already visible during early childhood (Chouinard, 2007; Harris, 2020).

588 Interestingly, these properties of questioning are already apparent in early forms  
589 of pointing. At the end of the first year, infants start producing pointing gestures  
590 that are either utility-driven or curiosity-driven (Begus & Southgate, 2012;  
591 Tomasello, Carpenter, & Liszkowski, 2007), and that have specific *focus*, as  
592 manifested by a deictic (i.e. focused on an object) gesture, as well as a *topic*.  
593 Imperative pointings communicate a *focused desire to get access* to an object: "I  
594 want that!". In the context of joint attention, declarative pointings communicate  
595 a *focused desire to share* with another person the perception of an object of  
596 interest: "look at that" (Lucca, 2020; Tomasello et al., 2007). Infants also use  
597 pointing to communicate a *focused curiosity* – for learning about an object. Just  
598 like preschool-aged children keep on asking questions until they receive an  
599 explanation (Frazier, Gelman, & Wellman, 2009) and adjust their questions to  
600 their informational goal (Ruggeri & Lombrozo, 2015), infants' tendency to point  
601 towards a novel object depends on whether they usually receive information  
602 upon producing that gesture or not (Begus & Southgate, 2012; Kovács, Tauzin,  
603 Téglás, Gergely, & Csibra, 2014). In addition, infants learn better the function  
604 and names of objects they have previously pointed towards (Begus, Gliga, &  
605 Southgate, 2014; Lucca & Wilbourn, 2016), which is also consistent with the  
606 idea they use these gestures to request information. We also know that 18-month  
607 children expect to receive information about object names in response to their  
608 pointing, not about their function (Lucca & Wilbourn, 2019). Granting that, in  
609 all these cases, inquisitive pointing expresses both a *focus* and a *topic* of

610uncertainty, these gestures appear to be the first developmental expression of a  
611genuine questioning ability<sup>2</sup>.

612

613Does this depend on a capacity to metarepresent knowledge and ignorance? Or  
614do toddlers' questions initially rely on non-conceptual forms of metacognition  
615(i.e., on a metacognitive feeling of curiosity)? It has been proposed that  
616questioning always presupposes an ability to conceptually represent the contrast  
617between present ignorance and a specific knowledge goal (Bromberger, 1988).  
618MF, however (as also does BQA), takes questioning *not* to presuppose a  
619*conceptual understanding of knowledge*. Questions only involve concept-based  
620metarepresentations if they focus on mental states ("what do you think about  
621this"? "Are you sure to know where the toy is?"). Two lines of evidence are  
622consistent with this idea.

623

624The first shows that young children answer a question more reliably if it is not  
625framed as a verbal report about what they know (Kim et al., 2016). Experiments  
626such as the classical appearance-reality task demonstrate that 3-year-olds fail to  
627track their own belief changes conceptually<sup>3</sup> (Gopnik & Astington, 1988). Such

---

<sup>3</sup><sup>22</sup>) Research on social referencing (Bazhydai, Westermann, & Parise, 2020; Goupil et al., 2016; Hembacher, 4deMayo, & Frank, 2020) and object directed babbling (Donnellan, Bannard, McGillion, Slocombe, & Matthews, 52020; Goldstein, Schwade, Briesch, & Syal, 2010) suggest other potential candidates, although more research is 6required to confirm whether these behaviors reflect both contrastive focus and topics, which would confirm that 7they reflect genuine questioning.

<sup>8</sup><sup>33</sup>) In a typical version of this task, having predicted that a Smarties box contained candies, participants find out 9that it actually contains pencils. When asked what they earlier thought was in the box, most children report that 10"they had always known" that it contained pencils.

628concept-based metacognitive failures can also be observed in the partial  
629knowledge paradigm (Rohwer, Kloo, & Perner, 2012). This paradigm collects  
630answers to a knowledge question in three conditions: children either have had  
631full visual access to one of two objects being hidden in a box, partial visual  
632access (they saw two objects, one of which would be hidden out of sight), or no  
633access at all. When asked in the partial knowledge condition *whether they know*  
634what is in the box, young children typically fail to verbally report their  
635ignorance. This type of response is intriguing, because non-verbal measures  
636independently suggest that young children do experience metacognitive feelings  
637of doubt (Balcomb & Gerken, 2008; Coughlin et al., 2014; Goupil et al., 2016).  
638A study inspired by a dual-process view of metacognition used the partial  
639knowledge paradigm to explore a possible dissociation between verbal report  
640and metacognitive feelings in this setting (Kim et al., 2016). Three and 4-year  
641old children were either asked to verbally report whether they knew which toy  
642was in a box, or to decide to inform another person about it. In the partial  
643knowledge condition, children were much more reliable in choosing to inform  
644than in verbally reporting what they knew<sup>4</sup>. This difference is consistent with a  
645dual-process view of questioning: reliably answering a question does not depend  
646on metarepresenting what one knows or does not know. It rather depends on  
647experiencing metacognitive feelings. Metarepresenting oneself as knowing, on

---

11<sup>4</sup>) No difference between reporting knowledge and decision to inform was found in the full and absent  
12knowledge condition, in line with previous findings that even 3-year-olds are able to verbally report their  
13ignorance in the absent knowledge condition (Rohwer, Kloo, & Perner, 2012).



648this view, depends on concept-based metacognition, whose dependence on  
649social norms and values is well-established (Frazier, Schwartz, & Metcalfe,  
6502021; Proust & Fortier, 2018).

651

652The second type of evidence comes from another study focusing on older  
653children and adults' answers to ambiguous questions – where the referent of the  
654question needs to be inferred from what the questioner allegedly knows or  
655ignores about a situation given their perceptual access (Aguirre, Brun, Reboul,  
656& Mascaro, 2022). It demonstrates that when interpreting epistemic questions,  
657both adults and children readily consider what the questioner can or cannot see,  
658but not necessarily what they know that they do not know. Thus, even adults do  
659not necessarily interpret questions in a "Socratic ignorance" mode (assessing  
660what the questioner knows that he does not know, Bromberger, 1988).  
661Furthermore, children's ability to interpret questions that have an ambiguous  
662focus was found to *not* correlate with their competence in passing second-order  
663false-belief tasks (Aguirre et al., 2022).

664

665Taken together, these findings suggest that – at a basic level - questioning does  
666not require metarepresenting knowledge and ignorance. It merely depends on a  
667prior detection of an informational gap and a learning affordance, associated  
668with the subjective experience of curiosity, and on representing, however  
669vaguely, a domain of alternative options; this requires metacognitive

670monitoring, but it does not require a concept-based metarepresentation of one's  
671own knowledge. Neither does the basic ability to respond to it (verbally or  
672otherwise).

673

**6744.c. *Conversational scaffolding of questioning.***

675The preceding section raises an important research issue: how do children  
676transition from feeling curious, to expressing non-verbal questions, and finally  
677putting questions into words? Much remains to be known about the various  
678cognitive and social factors involved (Lucca, 2020), but most authors take  
679questioning to be shaped by parental responsivity and glossing, and exposure to  
680specific sociocultural communicational practices (Butler, Ronfard, & Corriveau,  
6812020; Chouinard, 2007; Salomo & Liszkowski, 2013). Three types of parental  
682interventions might be particularly relevant.

683

684First, scaffolding infants' attention to their subjective uncertainty about a given  
685*focus* might enhance children's dispositions to be curious about their  
686environment, and indicate to them how they may communicate this to others. As  
687shown in Chouinard's monograph, the gestural expression of curiosity or doubt  
688by an infant is often glossed by the parent as a specific question (Chouinard,  
6892007). Caregivers also tend to ask more wh- and yes/no questions in response to  
690pointing compared to other behaviors (Wu & Gros-Louis, 2015). This suggests  
691that parental glossing can train infants to ask questions verbally by

692systematically mapping metacognitive feelings to specific inquisitive behaviors,  
693words and linguistic expressions, supporting a form of cross-situational learning  
694applied to mental states rather than external physical objects.

695

696Second, for a given focus, caregiver's glossing builds up classes of *contrastive*  
697*topics* (e.g., do you want to know how this is called? do you want to know how  
698this works?). Affective intonation may be especially efficient in establishing  
699relevant information in complement of syntactic and semantic cues (Roberts,  
7002012). Compare, for example, utterances of "Did *John* eat the cake?", i.e., [did  
701he – rather than Mary – eat the cake?], with "Did John eat *the cake*?" i.e., [did  
702John eat the cake rather than the banana?]).

703

704Third, caregivers' ability to provide satisfactory answers can train toddlers'  
705cognitive *habit* of questioning (Butler et al., 2020), and inform children about  
706who – amongst the person that surround them – is knowledgeable (Harris,  
7072020). What is conveyed, beyond a specific interactive episode, is a  
708conversational practice, whose specific goals are shaped by cultural constraints  
709(see next section). Through questioning and evaluating the informative gain  
710brought by the answers they receive, children can learn to satisfy their curiosity  
711in a context-sensitive fashion: their natural tendency to be curious can be  
712reinforced or discouraged. For instance, children ask more follow-up questions  
713when they receive explanations in response to an initial question (Frazier et al.,

7142009), and children whose parents provide more explanations are also more  
715likely to come up with their own explanation when they find that an answer was  
716unsatisfactory (Kurkul & Corriveau, 2018, also see below). Earlier in  
717development, correlations have been found between caregiver responsivity and  
718infant gesture use (Ger, Altınok, Liszkowski, & Küntay, 2018).

719

720On top of supporting the transition from non-verbal to verbal questioning,  
721conversational scaffolding may also have a deeper consequence. Non-verbal  
722questioning behaviors could be an important way through which children  
723transition from relying on metacognitive feelings to using metarepresentations.  
724This is because parents' responses to these communicative acts provide *discrete*  
725conceptual inputs (e.g., mentalistic words) that children can systematically map  
726onto analog metacognitive feelings. Linguistic input may thus support the  
727process through which a non-verbal questioning ability fueled by analog  
728metacognitive feelings is enriched by concept-based, metarepresentational  
729abilities. This hypothesis remains to be tested however.

730

#### 7314.d.) *Questioning as a communicational practice shaped by culture.*

732

733There is ample evidence that culture shapes metacognition (Kim, Proust, &  
734Shahaeian, 2018) and questioning (Callanan, Solis, Castañeda, & Jipson, 2020;  
735Gauvain & Munroe, 2020). Diversity begins with how situations are encoded

736and reasoned about. Different attention patterns are transmitted by caregivers to  
737children: they are predominantly holistic in Asia (relation-centered) and analytic  
738(object-centered) in Western societies (Nisbett, Choi, Peng, & Norenzayan,  
7392001). Similarly, although curiosity is a universal metacognitive feeling,  
740children should be curious about different things across culture, and be more or  
741less willing to ask questions of a certain kind, depending on the  
742communicational pragmatics of their social group. Although social norms  
743regulate everywhere the public expression of curiosity, implicit or explicit rules  
744concerning acceptable questioning foci differ across culture. In many rural  
745traditional societies, such as Malagasy (Ochs Keenan, 1976), Pacific islands –  
746including Samoa – (Ochs & Schieffelin, 1982/2001; Robbins & Rumsey, 2008),  
747Mopan Mayas of central America (Danziger, 2010) or Mexican Mayas (Le  
748Guen, 2018), others' whereabouts, beliefs or intentions are unsuitable  
749conversational topics. In these social groups, children progressively learn to use  
750indirect ways for obtaining information about what others think or do (Le Guen,  
7512018). In Western families, in contrast, infants' vocalizations and toddlers'  
752actions and utterances are considered as intentional and directly and verbally  
753glossed as such (Ochs & Schieffelin, 1982/2001; Chouinard, 2007).

754

755Similar socio-cognitive constraints shape acceptable ways of expressing and  
756answering questions. Communicative practices centered on nonverbal behaviors  
757such as gaze direction, gestures, subtle facial and postural changes, are favored

758in many traditional cultures for asking or responding (such as the Mayan and  
759Indian families studied in Rogoff et al., 1993). In contrast, middle-class US and  
760Turkish children are more likely to use speech, as do their respective caregivers  
761(Rogoff et al., 1993). Questioning and responding would also crucially vary with  
762more general constraints related to which partner – the informant or the child –  
763typically takes the responsibility for learning in a specific cultural setting  
764(Rogoff, 2003).

765

766In spite of the pragmatic differences discussed above, the overall frequency, and  
767broad topical categories (e.g., activity, location...) of children's questioning does  
768not appear to greatly vary with culture or socio-economic status (Callanan et al.,  
7692020; Gauvain, Munroe, & Beebe, 2013). For instance, a study reported that 3-  
770to 5-year-old Garifuna children from Belize, Newars children from Nepal,  
771Logoli children from Kenya and Samoan children ask as many information-  
772seeking questions as Western children from the US (Gauvain & Munroe, 2020;  
773Gauvain et al., 2013). This quantitative approach, however, revealed a  
774difference in the *type* of questions children asked. Children from these small-  
775scale traditional societies produced fewer explanatory questions than American  
776children (Gauvain et al., 2013). There is no evidence that such *cross-cultural*  
777differences in explanatory questioning behavior correlate with advantages in  
778reasoning or understanding facts about the world. Instead of interpreting  
779deviations from Western norms as deficits (which poses obvious problems, see

780Rogoff et al., 2017), such differences can be construed as reflections of wider  
781diversities in cultural norms and practices. Accordingly, Gauvain and Munroe  
782(2020) interpret this difference as a conjunction of two main factors. One is the  
783cultural value attached to the relations between children and adults: respect, a  
784social complement of age-based social distance, requires refraining from  
785requesting explanations from adults (an implicit rule that *all* Logoli children  
786followed several decades ago, when evidence was collected). In Western  
787societies, adults are eager to prepare their children to formal school education.  
788Parents' tutoring is seen as the best way to promote children's learning (Ochs &  
789Schieffelin, 1982/2001). Educated Western parents are prone to ask pedagogical  
790questions with known answers (Yu, Bonawitz, & Shafto, 2019). In contrast,  
791children from traditional societies are expected to cooperate with adults in  
792carrying out community tasks, but are left more autonomy in epistemic matters  
793than young Westerners. They readily learn by observing adults or older children  
794what they need to know about the causal structure of both physical and social  
795properties (Gaskins & Paradise, 2010).

796

797The frequency of explanatory questions also differs among Western children as  
798a function of their parents' socio-economical status (SES) (Kurkul & Corriveau,  
7992018; Tizard, Hughes, Carmichael, & Pinkerton, 1983). For instance, a recent  
800study found that, even though the ratio of explanatory and factual questions  
801remains constant across groups, middle-SES children ask twice the number of

802explanatory questions than low-SES children. Middle-SES caregivers are also  
803more likely to provide explanations, while low-SES families use circular  
804responses more frequently, e.g., "because that's the way it is" (Kurkul &  
805Corriveau, 2018), which may discourage further explanatory questioning.

806

807While the type of questions used by parents may not impact children's reasoning  
808when they are given exploratory autonomy, it may not be the case within  
809Western societies, where formal instruction prevails over observational learning,  
810and where children's learning opportunities largely depends on their educational  
811environment, including caregivers' availability and skills, as well as institutional  
812resources. A lack of practice in explanatory questioning might thus partially  
813explain low-SES children's disadvantage at school (Jones, Swaboda, & Ruggeri,  
8142020), where teachers typically expect that children should master this  
815communicative practice (Gauvain & Munroe, 2020). Relatedly, educational  
816studies have demonstrated that the type of questioning used at school predicts  
817school achievement. College students who seek teachers' help by asking  
818explanatory questions have higher achievements than those who do not: asking  
819for solutions – requesting expedient help – correlates instead with low  
820achievement (Karabenick, 2004; A. M. Ryan, Patrick, & Shim, 2005). Much  
821remains to be understood about the factors that may facilitate – or impair –  
822questioning in the classroom, as a function of children's socio-demographic and  
823cultural origin, and with the aim to better foster their learning in educational



824 settings that may enforce communicational practices that may – or may not –  
825 match their familial practices.

826

827 In summary, although children across the world have the same disposition to be  
828 curious, the social norms governing inquisitive communication and adult-  
829 children interactions deeply influence how children ask questions, in agreement  
830 with the idea that questioning depends on learned cultural practices adapted to  
831 local demands regarding communication and teaching.

832

833

## 834 **5) Conclusion**

835 In this paper, we argued that curiosity is a metacognitive feeling whose function  
836 is to motivate cognitive agents to adaptively fill their informational gaps. In  
837 conformity with current theorizing, as well as empirical and computational work  
838 about curiosity, the metacognitive view defended in this article singles out two  
839 monitoring steps: detecting a knowledge gap and identifying the probability of  
840 reducing this gap in a given context. When agents have experienced that  
841 curiosity leads to intrinsic rewards – the pleasure of learning –, they tend to be  
842 more curious, hence, explore and learn more (Oudeyer et al., 2016).  
843 Unfavorable learning environments, however, would symmetrically reduce  
844 curiosity, exploration and learning. Early forms of curiosity and inquisitive  
845 behaviors, then, can be analyzed as a form of self-regulatory metacognition:

846 monitoring their subjective uncertainty leads infants to strategically question  
847 knowledgeable others, which turns out to increase their learning rate. Epistemic  
848 questions, focusing on object properties or on explanatory relations, allow  
849 learners to reduce the distance to their epistemic goals (i.e. satisfy their curiosity  
850 toward a given focus), within the limits of culturally prevalent socio-cognitive  
851 constraints.

852

853 Given the documented link between efficient information-seeking and academic  
854 achievement, gaining better insights into the mechanisms that support curiosity  
855 and questioning during early childhood is crucial (Selmeczy, Ghetti, Zheng,  
856 Porter, & Trzesniewski, 2021; von Stumm, Hell, & Chamorro-Premuzic, 2011,  
857 Yu et al., 2018). Distinguishing experience-based (metacognitive feelings) from  
858 concept-based (metarepresentational) forms of curiosity can lead to diversified  
859 pedagogical practices, which together can enhance learners' motivation.

860

861 On the one hand, feelings of curiosity can be elicited and nurtured early on  
862 during spontaneous interactions with caregivers, for instance during play,  
863 through simple observation and reinforcement mechanisms. Adaptive  
864 questioning practices can similarly enhance childrens' curiosity, and reinforce  
865 their motivation to explore. If questioning is not conducted in accordance with  
866 the notion of proximal development, however, it tends to fail to induce it  
867 (Frazier et al., 2021).

868

869 Formal tutoring and explicit training, on the other hand, mainly rely on concept-  
870 based, controlled forms of curiosity. Some educational practices can be  
871 incompatible with curiosity, for instance when they emphasize teacher's  
872 authority, extrinsic motivation (for grades, rather than for knowledge) and social  
873 competition (R. M. Ryan & Deci, 2000). Emphasis on teacher-guided instruction  
874 over autonomous exploration, and on conformity over questioning and  
875 creativity, has resulted in Western teenagers being less avid learners (Hattie,  
876 2011; Kuhn, Modrek, & Sandoval, 2020). Conversely, explicitly  
877 metarepresenting what is known versus what is yet to be discovered has been  
878 found to enhance students' curiosity and their ability both to remember what  
879 they learned and to reason about it (Bjork, 2018). A question-and-answer  
880 method has been shown to be more effective than a text to achieve these goals  
881 (Iordanou, Kuhn, Matos, Shi, & Hemberger, 2019; Kuhn et al., 2020). Finally, a  
882 technique consisting in addressing questions to oneself, called "self-  
883 explanation", first used to train school children to understand what they read  
884 (McNamara & Magliano, 2009), has been successfully generalized to other  
885 educational fields (Rittle-Johnson, Loehr, & Durkin, 2017).

886

887 This diagnosis from educational studies is compatible with the experimental and  
888 theoretical work discussed in this paper, and emphasizes the importance of

889 understanding what curiosity is, how it relates to questioning, and how its early  
890 development influences life-long motivations to learn.

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### 897 **APPENDIX 1: When and how does curiosity develop?**

898 Young children already seek information as a function of what they already  
899 know, and how confident they are in what they know. This is specifically  
900 manifest in their selection of objects to play with. They engage in exploratory  
901 play as a function of how well they understand a specific situation, and as a  
902 function of how much information gain they can expect from it (Gweon, Pelton,  
903 Konopka, & Schulz, 2014; Lapidow et al., 2021; Schulz & Bonawitz, 2007;  
904 Siegel, Magid, Pelz, Tenenbaum, & Schulz, 2021). For instance, when they  
905 observe confounding evidence about how to activate a pop-up toy, five-year-old  
906 children prefer to keep on playing with this “old” toy rather than playing with a  
907 totally novel toy (Schulz & Bonawitz, 2007). Children also explore a novel toy  
908 more thoroughly when a teacher provided partial information, as opposed to full  
909 information, about its function (Gweon et al., 2014). In the language domain, 3-  
910 8 year-old children preferentially seek information about novel words when they

911are introduced to them in an ambiguous context that lead to referential  
912ambiguity (e.g., in the presence of two potential referents) (Zettersten &  
913Saffran, 2020).

914

915But when does curiosity emerge during human development, and perhaps most  
916importantly, how? In the main text, we allude to the proposal that surprise-based  
917explorations constitute a precursor for the development of curiosity-based  
918explorations (Perez & Feigenson, 2020; Vogl et al., 2019). If surprise is a  
919precursor of curiosity, then when in development do children transition from  
920surprise-based to curiosity-based explorations?

921

922We know that unpredictability enhances infant's attention (Kidd et al., 2012;  
923Meyer, Schaik, Poli, & Hunnius, 2022; Poli et al., 2020) and learning (Stahl &  
924Feigenson, 2015), and that attentional engagement during exploration predicts  
925how well infants learn novel object properties (Begus, Southgate, & Gliga,  
9262015). When 11-month-old infants observe events that violate their expectations  
927about object properties (e.g., a toy car that flies instead of obeying the laws of  
928gravity), they spend more time looking at these objects, and learn their novel  
929properties better (Stahl & Feigenson, 2015). Furthermore, when given the  
930opportunity to explore these objects, infants tend to try and reproduce the  
931surprising event, which can be seen as an attempt to test hypotheses about the  
932surprising object.

934 A rich interpretation of this type of behavior is that unexpected events pique  
935 infants' curiosity, leading them to subsequently engage in selective explorations  
936 to seek explanations. A leaner explanation that does not involve genuine  
937 curiosity, however, is equally possible: surprise may automatically enhance  
938 infants' attention towards objects that have unexpected properties given their  
939 prior knowledge. Observing surprising events may lead infants to revise their  
940 belief about the object's properties, and they may try to repeat the surprising  
941 event because they find it particularly rewarding and/or arousing. That is, maybe  
942 all infants do initially is generate expectations, revise their beliefs when  
943 expectations turn out to be false, and orient their attention selectively as a  
944 function of stimulus predictability. Thus, on the basis of this type of evidence,  
945 we cannot conclude on whether infants are curious per se (i.e., *want to know*  
946 whether the toy car flies or not), or whether they are merely surprised<sup>5</sup>.

947

948 When exactly - and how - infants start engaging in curiosity-driven explorations  
949 during development is thus an important open question. One possibility is that  
950 surprise sets the stage for the development of curiosity (Vogl et al., 2019):  
951 infants may progressively notice that when they engage in utility- and surprise-

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14<sup>5</sup>) Both interpretations can also explain recent results showing that infants no longer explore surprising objects (a  
15 toy car that appears to go through a wall) if an explanation is provided to them (there is a tunnel in the wall)  
16 (Perez & Feigenson, 2020). It may be that providing an explanation abolishes the appeal of the object: what is  
17 the point in exploring the car if you know that it won't display surprising properties? Thus, infants may not  
18 genuinely "want information" about the car when there is no explanation, the car could simply be more salient  
19 for them because it is likely to do unexpected – and thus potentially arousing – things in the future.

952driven explorations, they incidentally gain new knowledge (as in the clothing  
953example described above), and as a consequence, start exploring directly for this  
954purpose. A recent study supports this idea, as it found that infants' surprise  
955responses (i.e., longer looks) to unexpected events at 11 and 17-month-old was  
956correlated with curious traits measured via parental reports at age 3 (including  
957questions such as “my child devotes considerable effort trying to figure out  
958things that are confusing or unclear”) (Perez & Feigenson, 2021). These are  
959correlational findings, but they are at least compatible with the idea that surprise  
960is a developmental precursor to curiosity. Of note, a recent study found that,  
961while for adults curiosity mainly reflects the informational gain they expect in a  
962given context (a complex evaluation involving the two monitoring steps we  
963outlined above), 5- to 9-year-old children's curiosity correlates not only with  
964expected learning, but also with higher objective uncertainty and lower  
965surprise (Liquin, Callaway, & Lombrozo, 2021). It may thus be that younger  
966children's curiosity mainly depends on fluence-based elicitors, i.e., feelings such  
967as surprise, while adults' curiosity takes better advantage of computing learning  
968opportunities. Alternatively, reliably assessing expected learning in a given case  
969may change across development, and rely on various predictors integrating  
970knowledge and utility, exploration and exploitation.

971

972

973**APPENDIX 2. How should metacognition be defined?**

974

975 This appendix addresses the definitional debate between a single-process and a  
976 dual-process view of metacognition, whose main tenets were presented in  
977 section 2 in the main text. Arguments for each view will be summarized and  
978 discussed as follows. First, the reasons advanced in favour of a monistic,  
979 concept-based definition of metacognition will be articulated as three main  
980 objections against a dual view. After a critical discussion of these objections,  
981 the arguments for defending a dual-process definition of metacognition will be  
982 presented.

983

## 984 ARGUMENTS FOR A SINGLE-PROCESS VIEW OF METACOGNITION

985

### 986 1. *The first-order objection.*

987 A main reason for endorsing an exclusively conceptual approach to  
988 metacognition is the semantic analysis of the term "metacognition", where  
989 "metacognition" means "cognition about cognition", which implies that  
990 metacognition is to be equated with an ability to hold metarepresentations of  
991 one's own attitudes (Carruthers, 2016, 2018<sub>a,b</sub>; Perner, 2012; but see Carruthers,  
992 2021). Endorsing this definition leads to take subjective experiences of  
993 uncertainty as being merely "first-order" (Carruthers, 2016), because they are  
994 not explicitly *about* one's own mental states (Carruthers, 2016). Appropriately  
995 second-order metacognitive representations need to involve metarepresentations,



996i.e. explicit representations of one's own mental states and properties.

997

998 2. *The ubiquity objection* (Carruthers, 2016; Nagel, 2014; Perner, 2012).

999Under the admission of nonconceptual, affective forms of control as  
1000metacognitive, one should consider as metacognitive the multiple forms of  
1001forward models that subpersonally control and monitor our cognitive activity,  
1002including those that make sensorimotor control or multisensory conflict  
1003resolution possible. Granting that subpersonal forms of information (probability  
1004distributions) are used as input to metacognitive predictions, the objection goes,  
1005should not the multiple forms of forward models that subpersonally control and  
1006monitor our cognitive and motor activity also qualify as metacognitive  
1007(Carruthers 2016, 2018<sub>a,b</sub>)? For example, why should not the comparators that  
1008regulate conflicts across sensory channels, such as the visual-auditory conflict  
1009involved in the McGurk effect, be categorized as metacognitive (Nagel, 2014)?

1010

1011 3. *The irrelevance objection* (Carruthers, 2016).

1012This objection states that metacognitive monitoring is not involved in  
1013nonhumans' and infants' decisions to seek additional information instead of  
1014committing to a choice. Activities such as seeking information, trying – or  
1015declining – to remember, to discriminate, do not need to involve any form of

1016procedural evaluation. Non-human animals or human infants may instead  
1017decline a task or seek information simply because they lack a specific memory  
1018of the stimulus. Hence, decisions concerning memory depend on memory alone,  
1019not on meta-memory:

1020       *"For that one is disposed to act in one way if one has a memory, and in*  
1021       *another if one does not is just what it is to have or lack a memory. This*  
1022       *just describes the normal first-order causal role of memory in the*  
1023       *cognitive and decision-making processes of creatures that possess*  
1024       *memory-states."* (Carruthers, 2016, p.74).

1025

1026In addition, decisions to perform or to decline a memory task are argued to be  
1027sensitive to the likelihood of reward, not to the likelihood of cognitive success  
1028(i.e., epistemic uncertainty) (Carruthers, 2016, 2018<sub>a,b</sub>). A more economical  
1029account of infants' or nonhumans' opt-out or information seeking responses, so  
1030the argument goes, is a simple working memory decision based on reward  
1031probability that exclusively depends on the underlying first-order state.

1032

1033       II. RESPONSES TO THE OBJECTIONS.

1034

1035*1. Are feelings of confidence first-order ?*

1036 Addressing this objection requires clarifying what one means by "uncertainty".  
1037 On the one hand, uncertainty is *an objective property of the sensory input*. The  
1038 variability of relevant stimuli in the external world, for example, is an objective  
1039 source of uncertainty. The assessment through which the brain represents  
1040 probability distributions of *specific inputs* is clearly first-order. Granting that  
1041 there is noise in each informational channel, part of the objective uncertainty  
1042 originates in the perceptual system itself (Pouget, Drugowitsch, & Kepecs,  
1043 2016). This kind of uncertainty, as an objective characteristic of the sensory  
1044 input, does not yet qualify as a metacognitive signal.

1045

1046 On the other hand, uncertainty can also become a *subjective property of the*  
1047 *cognitive system*: the brain compares the variance in the evidence to stored values  
1048 (concerning for example onset of neural activity, convergence or disparity of  
1049 predictions) ; on this basis, it predicts (or estimates) the probability that a  
1050 perceptual or memorial task will be (or has been) correctly performed. In the  
1051 context of perceptual decision-making for instance, empirical evidence and  
1052 computational frameworks based on evidence-accumulation principles suggest  
1053 that decisions are made when perceptual evidence reaches a given threshold, and  
1054 that associated confidence relates to the distance between the decision threshold  
1055 and the maximum amount of evidence accumulated post-decisionally (Pleskac  
1056 & Busemeyer, 2010) or dynamically around (Pereira et al., 2021) or up until

1057(Kobe Desender, Donner, & Verguts, 2021) the time of the decision. The output  
1058of such comparators is a metacognitive feeling of confidence or doubt. Some  
1059researchers propose to call it "confidence" in contrast with "uncertainty" (Pouget  
1060et al., 2016). Its function is to predict the feasibility, or to monitor the desirable  
1061correction of a cognitive action, in order to select and motivate the congruent  
1062behavior (A Koriat, 2000).

1063

1064It should be observed that sensitivity to one's own subjective uncertainty does  
1065not merely result in retrospective feelings of confidence or doubt. It applies to  
1066the variety of metacognitive feelings and predictive functions summarized in  
1067Table 1 above. In summary, the information used to appraise the likelihood of  
1068one's own success in a given cognitive task (remembering, learning, etc.)  
1069consists in sets of probability distributions concerning predicted outcomes.  
1070While these predictions are performed through nonconscious Bayesian  
1071computations, they generate a conscious feeling with a given valence, intensity,  
1072and motivational strength, such as the feeling of retrospective confidence  
1073attached to a cognitive decision.

1074

1075Based on these considerations, one can conclude that the evaluative states  
1076involved in metacognition do not track "first-order" signals, i.e. objective

1077uncertainty, to the extent that such evaluations predict epistemic feasibility or  
1078correction from the agent's viewpoint in an occurrent context. They are based on  
1079heuristics formed by the agent across prior encounters with the task, and reflect  
1080a subjective state rather than an objective property of sensory inputs.

1081

10822. *The ubiquity objection: are all predictive models metacognitive?*

1083Addressing this objection requires focusing more closely on the function of  
1084metacognition. While there are nonconscious processes for revising one's own  
1085behavior – such as keeping one's balance (Klaus et al., 2020) or revising one's  
1086hand trajectory (Péllisson, Prablanc, Goodale, & Jeannerod, 1986) –,  
1087metacognition has the function of evaluating one's own informational states in  
1088order to control them. In other words, metacognition is specialized in the  
1089informational issues related to cognitive activities such as deciding,  
1090remembering or problem solving. To be sure: metacognitive evaluations do not  
1091predict the likely consequences of actions (e.g. grasping, catching...) but of  
1092cognitive actions (e.g., remembering, deciding). Hence metacognition does not  
1093adjudicate between sensory inputs, nor does it control and monitor sensorimotor  
1094activity. Its specific role consists in detecting and *incorporating relevant*  
1095*knowledge into one's present or future decisions and cognitive actions.*

1096

1097But why is this function not involved in resolving conflicts between  
1098sensorimotor channels, might the objector insist? A plausible response is that  
1099sensorimotor control is the evolutionary basis of cognitive control. In both cases,  
1100the dorsomedial frontal cortex (DMFC) stores forward models in order to  
1101predict sensorimotor and cognitive success. Forward models automatically  
1102compare expected and observed dynamics of an action, in particular its predicted  
1103timing. The neural structures implementing these forward models seem to have  
1104been later recruited for the control of thought, i.e., metacognitive control and  
1105monitoring (Egger, Remington, Chang, & Jazayeri, 2019; Ritz, Frömer, &  
1106Shenhav, 2020). The forward models for cognitive control, however, do not use  
1107sensorimotor cues to automatically correct behavior ; nor do they result in  
1108automatic compromises between sensory sources; they rather attempt to assess  
1109informational quality with an eye to its predicted value (rewards and risks  
1110incurred) with respect to commitments to specific alternatives, in ways that are  
1111subject-specific, and relate to the agents' current goals and motivations.

1112

11133. *The irrelevance objection: are metacognitive feelings necessary to explain*  
1114*children and non-human animal's information seeking?*

1115This objection fails to account for two central features of young children's use  
1116of opt-out, or information-seeking options (the discussion of comparative

1117evidence is left aside here as it has been addressed elsewhere, e.g., see Beran,  
11182019; Proust, 2019).

1119

1120First, adults and 3-yo children's subjective reports of confidence are related to  
1121opt-out and information seeking decisions (Coughlin et al., 2014; Desender et  
1122al., 2018). Assuming that functionally equivalent behaviours in slightly younger  
1123children should involve completely different mechanisms is not parsimonious.

1124

1125Second, children not only opt-out / seek advice when stimuli are ambiguous or  
1126when the task is difficult (i.e., as a function of objective uncertainty). They do so  
1127as a function of the quality of their memory or decisions (Balcomb & Gerken,  
11282008; Geurten & Bastin, 2018; Goupil et al., 2016), a subjective form of  
1129uncertainty. When 20-month-old children are provided with the opportunity to  
1130ask their caregiver for advice instead of pointing themselves towards the  
1131location of a hidden toy, they indeed predominantly use this option as  
1132memorization delay increases (Goupil et al., 2016). But in addition, and  
1133crucially, for equivalent memorization delays (i.e., similar objective task  
1134complexity), toddlers provided with the possibility to ask their caregiver for help  
1135(test group) make less errors than toddlers who were not shown that their  
1136caregiver could help (control group). If lack of memory – or, in Carruthers'  
1137words, "a basic questioning attitude" – drove these behaviors - rather than  
1138strategic adjustments relying on metacognitive feelings - one should reasonably

1139expect that children in the control group would also avoid responding whenever  
1140they "have a lack of memory". But they don't: children in the control group tend  
1141to respond by themselves, or occasionally to look away; furthermore, when they  
1142(very rarely) turn towards their caregivers spontaneously, this behavior is totally  
1143unrelated to their task performance and/or to difficulty. Thus, the failure of the  
1144cognitive activity of remembering does not automatically trigger help seeking in  
1145this age group.

1146

1147

### 1148III. ARGUMENTS FOR A DUAL DEFINITION OF METACOGNITION

1149Our responses to the objections given above are consistent with the general  
1150arguments offered in favor of dual process theories. According to this family of  
1151theories, an impulsive evaluative "System 1" generates a quick response, based  
1152on independent parallel frugal heuristics. A deliberately controlled "System 2"  
1153handles its evaluations serially, takes time to operate, consumes more working  
1154memory resources than System 1, and heavily relies on conceptual resources.  
1155While the representations in System 2 are characteristically conscious and  
1156volitional, System 1 representations are typically unconscious and influence  
1157behavior automatically (Shea et al, 2014, Reder, 1996, but see Koriat, 2000).

1158

1159More specific arguments in favor of metacognitive duality range from  
1160comparative and developmental evidence, to behavioural and neural



1161 dissociations in human cognitive decision-making.

- 1162 1. Comparative evidence indicates that nonhumans (rodents, primates)  
1163 are able to reliably evaluate their perception or their memory in a  
1164 predictive or a retrospective way (Beran, 2019; Couchman, Beran,  
1165 Coutinho, Boomer, & David Smith, 2013; Kepecs & Mainen, 2012;  
1166 Proust, 2019).
- 1167 2. A hierarchy among human brain systems reflects the evolution of  
1168 control mechanisms towards enhanced exploratory flexibility  
1169 (Koechlin, Summerfield, E, & C, 2007; Rouault & Koechlin, 2018).
- 1170 3. In human ontogeny, children display behavioral markers suggesting  
1171 that they experience feelings of curiosity and confidence before they  
1172 can conceptually represent themselves as having these mental states  
1173 (Bazhydai & Westermann, 2021; Goupil & Kouider, 2019).
- 1174 4. In human adults, dissociations have been documented in  
1175 metacognitive monitoring according to task demands, between  
1176 feeling-based and concept-based incompatible evaluations (Koriat &  
1177 Ackerman, 2010; Nussinson & Koriat, 2008). Neural signatures  
1178 likewise distinguish deliberate, conscious error monitoring from  
1179 automatic, unconscious error monitoring (Nieuwenhuis, Ridderinkhof,  
1180 Blom, Band, & Kok, 2001; Yeung & Summerfield, 2012).
- 1181 5. Clinical research also suggests dissociations between core  
1182 metacognitive regulatory processes and the metacognitive sensitivity

1183 expressed in subjective reports (Charles et al., 2017; Metcalfe, van  
1184 Snellenberg, DeRosse, Balsam, & Malhotra, 2012; Nicholson,  
1185 Williams, Lind, Grainger, & Carruthers, 2020). For instance, patients  
1186 with schizophrenia show altered error-monitoring when performing  
1187 decisions on the basis of supraliminal stimuli, but preserved error  
1188 monitoring for subliminal stimuli (Charles et al., 2017). Children and  
1189 adolescents with autism spectrum disorder show impairments in  
1190 mindreading tasks (that tap into metarepresentational abilities), but not  
1191 in post-decisional gambling tasks (that require them to evaluate the  
1192 likelihood that their decision was correct, a core metacognitive ability)  
1193 (Nicholson et al., 2020, but see Koren, Seidman, Goldsmith, &  
1194 Harvey, 2006).

1195 6. In collective cognitive decision-making, individual epistemic feelings  
1196 need to be collected for optimal reliability in deliberation, but sharing  
1197 one's confidence with others requires complex interpersonal  
1198 calibration processes that are constantly adjusted and re-negotiated  
1199 through conversational alignment (Bang et al., 2017; Fusaroli et al.,  
1200 2012).

1201

1202 Collectively, these lines of evidence show that there is an important functional  
1203 distinction between system-1/core/procedural versus  
1204 system-2/deliberate/conceptual forms of metacognition (Goupil & Kouider,

12052019; Koriat & Levy-Sadot, 1999; Proust, 2012; Shea et al., 2014).

1206

1207

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1210

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