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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)**

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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_{a,b}). 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

2912.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

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

561

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

563

564Questioning is often produced to reduce S's subjective uncertainty, or to test R's
565knowledge about a given subject matter, but it can also be used to provoke
566specific non-epistemic responses from R. Typically, in English, the function of
567the 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)¹.

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

¹) 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 ability².

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 conceptually³ (Gopnik & Astington, 1988). Such

3²²) 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.

8³³) 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 knew⁴. 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

11⁴) 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

674***4.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:

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

852

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

860

861On the one hand, feelings of curiosity can be elicited and nurtured early on
862during spontaneous interactions with caregivers, for instance during play,
863through simple observation and reinforcement mechanisms. Adaptive
864questioning practices can similarly enhance childrens' curiosity, and reinforce
865their motivation to explore. If questioning is not conducted in accordance with
866the 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.

891

892

893

894

895

896

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 surprised⁵.

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-

14⁵) 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_{a,b}; 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_{a,b})? 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_{a,b}). 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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