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A transdisciplinary view on curiosity beyond linguistic humans: animals, infants, and artificial intelligence

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ABSTRACT

Curiosity is a core driver for life-long learning, problem-solving and decision-making. In a broad sense, curiosity is defined as the intrinsically motivated acquisition of novel information. Despite a decades-long history of curiosity research and the earliest human theories arising from studies of laboratory rodents, curiosity has mainly been considered in two camps: 'linguistic human' and 'other'. This is despite psychology being heritable, and there are many continuities in cognitive capacities across the animal kingdom. Boundary-pushing cross-disciplinary debates on curiosity are lacking, and the relative exclusion of pre-linguistic infants and non-human animals has led to a scientific impasse which more broadly impedes the development of artificially intelligent systems modelled on curiosity in natural agents. In this review, we synthesize literature across multiple disciplines that have studied curiosity in non-verbal systems. By highlighting how similar findings have been produced across the separate disciplines of animal behaviour, developmental psychology, neuroscience, and computational cognition, we discuss how this can be used to advance our understanding of curiosity. We propose, for the first time, how features of curiosity could be quantified and therefore studied more operationally across systems: across different species, developmental stages, and natural or artificial agents.

Key words: curiosity, intrinsic motivation, exploration, information processing, developmental psychology, animal cognition, computational cognition.

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I. INTRODUCTION

Curiosity is an intrinsic drive to acquire novel information and is seen as a defining human characteristic (Barto, 2013; Markey & Loewenstein, 2014; Dean, Tulsiani & Gupta, 2020). Curiosity and learning are fundamentally linked; learning is defined as a relatively permanent change in behaviour due to lived experience (Washburne, 1936; Lachman, 1997), so curiosity drives the experiences from which we need to learn. Furthermore, curiosity is fundamentally linked to exploration and can be seen as the driving force behind it (Berlyne, 1950). Curiosity is often associated with 'humanness'. From watching YouTube videos, reading books, or travelling, many of us regularly engage in activities primarily fuelled by curiosity that do not have an extrinsic reward or immediate relevance to our survival (Markey & Loewenstein, 2014). This constant drive to explore and make sense of our surroundings is crucial for educational and creative activities, but also is seen evolutionarily as a capacity that enabled humans to be highly adaptive and survive in challenging environments (Gallagher & Lopez, 2007; Hardy III, Ness & Mecca, 2017; Shin & Kim, 2019). Despite a human focus, curiosity is in fact not unique to our species, and to understand better the evolutionary significance of curiosity and its practical application to artificially intelligent systems, we must give more credence to curiosity in all its forms.

Most empirical assessments of curiosity to date have been on humans performing language-based tasks. Pre-linguistic infants/children and non-human animals (hereafter animals) have been overlooked, which is ironic given that the earliest studies of curiosity were performed on laboratory rodents (Berlyne, 1955, 1966; Glickman & Hartz, 1964). Perhaps because older humans have the capacity to self-report their subjective experience of curiosity (i.e. describe thoughts and feelings), behavioural observations of curiosity have been relatively overlooked. These taxonomic and methodological restrictions have led to a failure to evaluate the potential continuity of curiosity across phylogeny. But doing so will be key to our understanding of evolutionary selection pressures shaping it. Moreover, focusing on linguistic humans also overlooks the role of curiosity in infants and younger children, even though the pressure to acquire novel information and adapt to the environment is considerably higher early in life (Twomey & Westermann, 2018; Oudeyer & Smith, 2016). Our current restricted knowledge on curiosity as a mental tool, critical for learning in developing individuals, is striking and research taking the developmental perspective of such traits will uncover its adaptive function in humans and other animals.

The overarching aim of this review is to put forward the scientific study of curiosity, across disciplines that traditionally have been siloed by differential methods and standpoints. We reveal how the *status quo* in curiosity research (i.e. a focus on linguistic humans) has led to significant gaps in knowledge. To do so, we dedicate the first part of the article to showing that the terminology and definitions surrounding curiosity partly have philosophical and/or historical reasons, which divided the topic into two camps with little interconnection between research fields. We then discuss in what ways curiosity is conflated with other terms, i.e. intrinsic motivation and exploration tendency, and provide a summary of the various definitions of curiosity featured in the disciplinary literature. Our main contribution is to describe what is currently known about curiosity beyond linguistic humans, and how a greater focus on diverse systems will advance the field by paying attention to the biological functions of curiosity in non-linguistic beings. Ultimately, we argue that curiosity is not a single trait, but has multiple components, comparable to a modern view of intelligence (Gottfredson, 1998; Nyborg, 2003; Warner, 2007). Finally, we propose future directions for studying curiosity within a comparative framework, moving beyond traditional disciplinary borders.

II. HOW THE HISTORY OF DEFINITIONS HAS IMPEDED STUDIES ON NON-HUMAN CURIOSITY

It is difficult to parse the relative contributions of animal and human empirical research in the earliest works on curiosity, where initial studies may have been undertaken on rodents then theories subsequently contextualized for humans. We do not provide a very detailed historical account here but instead highlight the most salient points. It is difficult to pinpoint exactly when the scientific study of curiosity began, but in the 19th century, William James (commonly referred to as the 'father of psychology') described curiosity as the motivation *to learn what one does not know* (James, 1890) and set the stage in filing curiosity into two distinct types: standpoint 1 acknowledged a biological function of curiosity as an instinct-driven behaviour, whereas standpoint 2 was more complex and posited that curiosity relies on language. By the beginning of the 20th century, curiosity was widely seen as a basic biological drive in humans and animals alike, alongside other drives like hunger or sexual appetite. Curiosity as a drive to explore was based on animal studies documenting their exploratory behaviours in the absence of any external rewards (usually food, e.g. Nissen, 1931).

A paradigm shift came when Berlyne (1960) moved away from curiosity as a basic biological drive, but like James also distinguished between two types of curiosity. First, Berlyne distinguished perceptual from epistemic curiosity. Perceptual curiosity refers to interest in novel, strange or ambiguous perceptual stimuli which motivates visual and sensory inspection. By contrast, epistemic curiosity is the desire for knowledge or intellectual information (which applied mainly to humans). Later, Berlyne developed these concepts into diversive and specific curiosity. For Berlyne, diversive curiosity was an individual's 'taste for adventure', despite the risks this may entail. On the other hand, specific curiosity is the motivation to explore a specific object or problem with the goal of understanding it, thus resembling his initial view of perceptual curiosity. Berlyne also introduced the concept of various 'collative variables' that can trigger human curiosity, such as novelty, uncertainty, or complexity, and as we will see, today these factors are integrated into research on curiosity across model systems. Berlyne's theory proposed that curiosity requires an individual to use their cognition to compare different sources of information: newly perceived information against stored memories and understanding. Several other prominent curiosity theories arose from Berlyne's theoretical framework. For example, Loewenstein (1994) suggested that an information gap was the fundamental pre-requisite of curiosity; there is a disparity between an individual's current knowledge and their desired level of understanding. This information gap generates a state of deprivation and creates a necessity for learning to reduce the gap (Markey & Loewenstein, 2014). Other psychologists such as Day (1982) suggested that the information gap needs to be optimally sized to result in curiosity. Too large a gap may cause anxiety, and too short a gap may not be sufficient to trigger the need for information-seeking behaviours. As we shall demonstrate in this review, the information gap theory repeatedly appears in studies of curiosity across disciplines.

Across a historical literature base, curiosity has mainly been studied from the standpoint of adult humans and their desire to 'know' (see overview by Benedict, 2001), and various scientific disciplines or sub-fields have focused on categorization of curiosity rather than taking a wide view (for example by addressing Tinbergen's four questions; Tinbergen, 1963). For example, psychologists and neuroscientists appear to have emphasized the underlying motivational processes of curiosity, whereas ethologists and computational scientists have focused more on novelty-seeking drivers.

Alongside the challenge of defining curiosity and the lack of a theoretical framework to study it, several methodological posits in the field of comparative psychology have limited the empirical investigation of curiosity in animals (see Wynne, 2004; Shettleworth, 2012). Some methodological issues have been explored extensively in the philosophical literature [including Ockham's Razor (see Kelly, 2004; Shettleworth, 2010; Halina, 2015; Sober, 2015; Dacey, 2017; Andrews, 2020)], with anti-anthropocentrism and Morgan's Canon most pertinent to our review because they have commonly been used as pretences to block the ascription of 'higher' psychological predicates such as curiosity to other animals. In brief, anti-anthropocentrism is the principle whereby researchers '*reject the attribution of human traits to other animals, usually with the implication it is done without solid justification*' (Shettleworth, 2010, p. 477). Indeed, it is widely agreed upon by biologists that anthropomorphizing animals does not make for good science. However, in certain instances it could produce an opposite problem in comparative psychology: a 'neganthropomorphic fallacy' (Levin, 2019). If we deny the ascription of cognitive and psychological predicates to systems that might genuinely possess them, we may reinforce anthropocentrism or human exceptionalism. Instead, it has been argued that we should acknowledge the phylogenetically rich interconnections that exist physiologically and psychologically (Levin, 2019).

The most parsimonious explanation for animal minds has become known as 'Morgan's Canon', which states that no animal activity should be interpreted as higher psychological processes, if it can be interpreted instead by processes which are seen as lower in the scale of psychological evolution (Morgan, 1903). Indeed, Morgan's Canon is now ubiquitous in the field of comparative psychology, and many anecdotes and stories are told to discourage early scholars from engaging in the reasoning that leads to positing more psychological richness in animals than is 'actually' present. According to Morgan's Canon, comparative psychologists should avoid using rich psychological terms such as 'thinking', 'reasoning', 'evaluating', and indeed 'being curious' and instead use simpler ones.

We argue that the tendency to exclude (indeed, actively prohibit) rich psychological terms has come to impede, not progress, the field of comparative psychology and especially hinders comparative approaches beyond our own species. While Morgan's Canon has been influential, a growing chorus of science philosophers and theoreticians have called for the jettisoning of the principle (see Sober, 2015; Andrews, 2020) because it can oversimplify our understanding of animal psychology and inhibit scientific progress (Mikhalevich, Powell & Logan, 2017; Andrews, 2020). In a similar manner to how the study of animal emotions has recently begun to shed light on animal psychology and deep evolutionary convergences, we predict that loosening the broad prohibition on 'animal curiosity' will open new avenues for future research. Indeed, in the scientific study of animal minds it is important to have a concerted and self-conscious effort to identify biases and prejudices that might negatively influence experimental paradigms and scientific interpretation, but this is a requirement of all empirical science. We thus argue that should advance the study of animal curiosity without becoming overly concerned with violating Morgan's Canon.

III. CURIOSITY BEYOND LINGUISTIC HUMANS

In this section we discuss the different viewpoints on curiosity where it has been studied in non-linguistic agents: animals, human pre-verbal infants and artificial intelligences. This body of research thus derives from interdisciplinary crossroads between developmental psychology, neuroscience, animal cognition and computational cognition. We will thereafter debate in what ways we can identify similarities and discrepancies across systems and propose future frameworks moving the field beyond disciplinary boundaries to advance our scientific understanding of curiosity across intelligent agents.

(1) Curiosity in animals

Just like humans, animals explore their environment (and components therein) for the sake of the activity itself (Byrne, 2013), and as described earlier, animal studies formed the basis for later research of curiosity in humans, helping to shape multiple early human theories (see Section II). It therefore seems ironic that over time, human and animal studies of curiosity have diverged and perhaps in doing so have moved away from meaningful evolutionary comparisons. This is the case despite the fact that ethologists, behavioural ecologists and zoologists have long measured behaviours potentially interlinked with curiosity, such as neophilia (attraction to novelty) and exploration tendency (Glickman & Sroges, 1966; Heinrich, 1995; Greenberg, 2003; Kendal, Coe & Laland, 2005; Bergman & Kitchen, 2009; Mettke-Hofmann, 2014; Forss *et al.*, 2015; Griffin, Netto & Peneaux, 2017; Damerius *et al.*, 2017*b*).

Because researchers have been tentative in their use of the term curiosity due to the risk of anthropomorphism (see Section II) and the challenge empirically to assign intrinsic motivation to animals, the operating definition is kept broad: *the motivation to seek information and learn about something unfamiliar* (Table 1). This definition derives from psychology and Berlyne's (1966) work on perceptual curiosity and novel information-seeking in rats. To underline that curious behaviour diverges from other activities, which directly answer biological needs, some behavioural scientists have imposed a further criterion for an exploratory behaviour to classify as curiosity: exploration and novelty-seeking *needs to be outside the context of general survival activities*, such as feeding or searching for protection or mates (Byrne, 2013; Kidd & Hayden, 2015).

Considering the Darwinian position that shared evolutionary history incorporates the heritability of psychological traits and the fact that behaviours interlinked with curiosity have been demonstrated across all major animal taxa [fish (Bisazza, Lippolis & Vallortigara, 2001; Martins *et al.*, 2012), amphibians (Carlson & Langkilde, 2013; Kelleher, Silla & Byrne, 2018), reptiles (Bashaw *et al.*, 2016; Siviter *et al.*, 2017), various mammals (Bergman & Kitchen, 2009; Blaser & Heyser, 2015; Carter *et al.*, 2018; Powell *et al.*, 2004) and birds

Table 1. Common definitions of curiosity across scientific disciplines.

Definition of curiosity	Suggested functions	References	Scientific discipline
A state of alert wakefulness (in the human infant)	Deep attention paid to the wider environment	Beiser (1984)	Developmental psychology
An improvement of prediction for getting knowledge or reduction in uncertainty	Reducing uncertainty and seeking information	Schmidhuber (1991*b*); Oudeyer & Kaplan (2007); Friston *et al.* (2017); Kidd *et al.* (2012)	Neuroscience
The motivation to seek information about something unfamiliar (beyond general survival activities)	Motivates latent learning	Berlyne (1950); Loewenstein (1994); Byrne (2013); Damerius *et al.* (2017*a*); Wang & Hayden (2021); Forss *et al.* (2022)	Animal cognition
The intrinsic motivation to explore autonomously and continuously novel space-states/goals where the learning progress can be maximized over time	Motivates lifelong learning of new information and skills	Barto (2013); Lungarella *et al.* (2003); Oudeyer & Kaplan (2009); Santucci *et al.* (2020); Schillaci *et al.* (2020)	Computational modelling

(Huber, Rechberger & Taborsky, 2001; Mettke-Hofmann *et al.*, 2006; O'Hara *et al.*, 2017)], an evolutionary continuity of curiosity becomes undeniable. Moreover, since information processing is central to all cognitive abilities, and animal minds represent biological information-processing devices, identifying curiosity in animals can reveal in what way they perceive and are motivated to process new information. There have been three broad approaches to studying curiosity in animals which we shall detail here: (*i*) exploration of a benign novel object or novel stimulus; (*ii*) exploring a specific problem/task; and (*iii*) responses to abstract information.

(*a*) *Novel object/stimulus paradigm*

Because we cannot ask animals how curious they feel (in contrast to self-reports of curiosity in humans; see Gross, Zedelius & Schooler, 2020), behaviour is the most common proxy for curiosity in animals. More specifically, researchers have often experimentally induced curiosity by introducing a novel object (or other stimulus like a scent or sound) into the animal's familiar environment to infer motivation to explore and gather information about something previously unknown (Glickman & Sroges, 1966; Bacon, 1980; Damerius *et al.*, 2017*b*; Hall *et al.*, 2018; Forss *et al.*, 2022; Forss & Willems, 2022). In most cases, the novel object is inert; while it can be manipulated and perhaps destroyed, it fundamentally differs from 'puzzles' which are task-based and can be solved with or without retaining a food reward (see Section III.1.*b*). Traditionally, the animal's latency (i.e. duration of time) to approach a novel object is taken as a relative measure of their attraction towards novelty (neophilia) (Day *et al.*, 2003; Greenberg, 2003; Kaulfuß & Mills, 2008; Inzani, Kelley & Boogert, 2022). It is of course possible an animal will instead avoid the novel object, a behavioural response referred to as neophobia (Greenberg, 1990; Fox & Millam, 2007; Greggor *et al.*, 2016; Forss *et al.*, 2015; Miller *et al.*, 2022; Szabo & Ringler, 2023).

Critics of the novel object paradigm argue that approaching a novel object does not demonstrate that an animal obtained or learned any new knowledge (Bevins & Besheer, 2006; Takola *et al.*, 2021), hence does not fulfil some of the definitions of curiosity imposed by some disciplinary definitions and not seeking out novelty (i.e. retreating from a novel object or remaining neutral towards it) cannot rule out an animal's potential state of curiosity even if it refrains from physical exploration. Therefore, some scholars have argued that for animals, especially wild ones, whose environments pose existential risks, the degree an animal can display curiosity is interconnected with its levels of neophobia (Greenberg, 2003; Mettke-Hofmann, 2014; Forss, Koski & van Schaik, 2017). As such, an animal can possess both high levels of intrinsic neophobia, serving as a protection mechanism to avoid danger, and simultaneously have a high intrinsic motivation to explore (Reader, 2015; Moretti *et al.*, 2015; Forss *et al.*, 2017). In other words, for animals, expression of curiosity may be interlinked with their capacity to overcome initial neophobia (Forss *et al.*, 2017; Forss & Willems, 2022). Consequently, we argue that risk levels in a species' habitat (synonymous with 'harshness'; Roth, LaDage & Pravosudov, 2010) may have played a central role in the evolution of curiosity (see Section III.1.*d*).

Beyond solely considering initial motivation to approach and seek out novelty (neophobia/ neophilia), how long and in what way animals explore novel objects in terms of the diversity of manipulation actions, duration, and persistence to explore, presents another axis of how to measure 'observable curiosity' (Pisula, 2020; Damerius *et al.*, 2017*b*; Forss *et al.*, 2022; Birchmeier *et al.*, 2023). As such, object manipulation has the potential to deliver more descriptive data to our understanding of their motivation to gather new information. For example, meerkats (*Suricata suricatta*) explored low-odour novel items more than novel items emitting an odour (Birchmeier *et al.*, 2023). This supports the idea that the animals behaved to gain information about the novel cue, since in situations when they cannot receive enough information through their main sensory modality of olfaction, they proceeded with physical object exploration to discover properties of the novel cue. Thus, when studying curiosity in animals we need to consider species-specific, evolved sensory channels through which environmental stimuli are processed.

A recent study, which aimed at teasing apart separate behavioural indicators of curiosity and exploration in bottlenose dolphins (*Tursiops truncatus*) and European starlings (*Sturnus vulgaris*), may offer new methodological insights to the classic novel object paradigm (Hausberger *et al.*, 2021). The authors presented these species with species-specific stimuli (for dolphins, photographs of unfamiliar dolphins or plain water as a control; for starlings, the songs of unfamiliar starlings and of humpback whales) and observed a period of intense looking towards the stimuli *before* movement towards them. Thus, Hausberger *et al.* (2021) argued that a period of curiosity (looking) came before exploration (moving towards). If this is the case and can be replicated in other species, this methodology may complement the classic novel object test by capturing a precursive period of curiosity.

(*b*) *Problem-solving paradigm*

Despite great efforts to uncover various animal species' cognitive capacities to solve problems and innovate, curiosity has been overlooked within this body of the animal cognition literature. From the small amount of research thus far, orangutans (*Pongo abelii* and *Pongo pygmaeus*) that scored as more curious (assessed through multiple novel stimulus paradigms) and were more human oriented also used more diverse exploratory actions and were better at solving physical cognition problems (Damerius *et al.*, 2017*a*,*b*). This could indicate orangutans possess a 'curiosity drive' related to physical cognitive challenges. Earlier work on primates showed that rhesus macaques (*Macaca mulatta*) manipulate task-based objects with no food reward, for the apparent sake of learning how to complete the task (Davis, Settlage & Harlow, 1950; Butler, 1954). These types of classical cognitive laboratory study do not fit neatly into a novel object nor abstract information paradigm, and so we have placed them as a problem-solving paradigm. In studies of this kind, animals very often invest time to 'work' on a puzzle without immediate reward. There are also other studies of contra freeloading (working for food when free food is simultaneously available) performed with animals across laboratory, farm, sanctuary, and zoo settings that we will not discuss further here [for work for food despite its free availability see Inglis, Forkman & Lazarus (1997); for work as reward see Franks (2019)].

(*c*) *Abstract information paradigm*

Thus far, we have discussed how curiosity has been speculatively induced in animals by providing them with novel objects or specific problem-solving puzzles. A limitation of these classical paradigms is trying to demonstrate that the demand for information scales with the amount of information available, and it has been challenging to link knowledge gain to a curiosity-driven search for information. In addition, the information an animal gains from being curious may lead to significant future rewards, so is not truly unrewarding. However, this problem is not unique to animals; curiosity may potentially drive infants to engage with objects in their environment in the absence of an immediate reward but there is a longer-term payoff to this knowledge. As such, exploratory actions can be argued to be evolutionary adaptations for learning progress.

A recent empirical study has convincingly demonstrated that primates will sacrifice a current reward to gather new information (Wang & Hayden, 2019). This has been achieved by giving rhesus macaques a computerized gambling task and testing how much value they placed on finding out if they had gambled correctly (Wang & Hayden, 2019). The design was similar to humans paying for answers to quiz questions; knowing the answers *post hoc* satisfies the subjective feeling of human curiosity (Friston *et al*., 2017; Noordewier & van Dijk, 2017). Macaques sacrificed a water reward to find out what would have happened if they gambled correctly, even though they could not use this information to change the outcome. Because the animals tested in this paradigm passed the criteria of (*i*) sacrificing reward to obtain information, (*ii*) obtaining information that led to no immediate benefit, and (*iii*) sacrificing reward proportional to the amount of information available, Wang & Hayden (2019) argued this was a demonstration of non-human primates possessing human-like curiosity.

(*d*) *Animal curiosity, ecology, and habitat*

Ecology, especially in form of habitat risk, is predicted to impact the level of curiosity both among and within species, and so research on animal curiosity faces the challenge of vast variation between different environments (Mettke-Hofmann, 2014; Forss *et al*., 2015; Barrett, Stanton & Benson-Amram, 2019; Inzani *et al*., 2022). In theory, any animal should benefit from gathering new information regarding food sources, social partners, predators, and so on; one would therefore expect natural selection to favour a mechanism, like curiosity, to maximize learning from one's environment (Byrne, 2013; Forss *et al*., 2017). However, the great risks associated with natural environments constrain selection on curiosity, as wild animals must be vigilant for predators and rivals and thus engaging in time-intensive exploration is a relatively costly activity that must be balanced with key survival behaviours like foraging (Forss *et al*., 2015; van Schaik *et al*., 2016).

One of the most extreme environmental discrepancies scientists have quantified is the difference between the wild and captivity (Clark *et al*., 2023). Unlike wild conspecifics, captive animals experience less-hazardous environments and intriguingly, captivity appears to boost curiosity in mammals and birds [orangutans (Forss *et al*., 2015; Damerius *et al*., 2017*b*), vervet monkeys (*Chlorocebus pygerythrus*) (Forss *et al*., 2022), spotted hyaenas (*Crocuta crocuta*) (Benson-Amram, Weldele & Holekamp, 2013), rats (*Rattus norvegicus*), grey short-tailed opossums (*Monodelphis domestica*) (Pisula *et al*., 2012), meerkats (Birchmeier *et al*., 2023) and Goffin's cockatoos (*Cacatua goffiniana*) (Rössler *et al*., 2020)]. Such a captivity effect seems counterintuitive, given that wild animals presumably have a greater need to seek new information than captive animals. Perhaps this phenomenon is due to captive animals having relatively more time to spend being curious as opposed to performing essential survival activities (Kummer & Goodall, 1985). Connected to this is a reduction in cognitive load and distress due to a risk-free and less survival-focused life in captive settings. Even among free-ranging animals that are exposed to humans, habituation levels and repeated experience with man-made, artificial artifacts can additionally trigger curiosity in animals (van de Waal & Bshary, 2011; Forss *et al*., 2022).

From what we currently know from psychology, responses to the stimuli eliciting human curiosity follow a U-shaped curve, with a peak for stimuli of intermediate familiarity (see Section III.2.*a*; for a review see Kidd & Hayden, 2015). This suggests that a (human) subject possesses some background experience against which presented stimuli are evaluated, and accordingly triggers variations in response. If we assume that animal curiosity follows same trajectory as humans, animals from different habitats (such as the contrast between wild and captive) will possess very different reference points on novelty, due to their increased experience with human-made materials and artifacts compared to wild individuals, and thus this experience effect may explain part of the differences in intraspecific variation in curiosity observed between environments. As such, cognitive ecologists uncovering how different socio-ecological conditions influence how animals differ in their perception of their environment can help us to understand the evolutionary pathways to curiosity. In the case of captive great apes, within the same species, exposure to humans and varying degrees of enculturation (i.e. strong human cultural influences during development) seem to influence an individual's levels of curiosity (Bering, 2004; Tomasello & Call, 2004; Russell *et al.*, 2011; Damerius *et al.*, 2017*b*). Even though such claims remain to be probed thoroughly, they provide an intriguing perspective of an evolutionary continuum of curiosity and its social and cultural influences during development.

(*e*) *Neuroscientific research on animals*

Neuroscientific work on animal curiosity (or at least linked to curiosity, for example, exploration) has been restricted to a handful of models [rodents, the *Aplysia* sea slug, and some primates (Ferdowsian, 2011; Wendler, 2014)]. However, research addressing the neuroscience of curiosity in non-human animals is starting to gain pace using concepts such as uncertainty, novelty, and reward. For example, macaques consistently prefer to receive information in advance about an upcoming reward (a small or large amount of water), even when prior information does not influence the size of reward outcome (Bromberg-Martin & Hikosaka, 2009). Another study on macaques revealed that intrinsic motivation to seek informational reward cues derives from both uncertainty reduction and conditioned reinforcement independently of offered extrinsic rewards (Daddaoua, Lopes & Gottlieb, 2016). Taken together, these results indicate that non-human primates prefer to resolve uncertainty when they can, and thus support the information gap theory of curiosity (Loewenstein, 1994).

In both humans and some animal models (e.g. rodents and non-human primates) the dopaminergic system and prefrontal cortex are suggestively involved in curiosity and novelty-seeking behaviours (Bromberg-Martin & Hikosaka, 2009; Blanchard, Hayden & Bromberg-Martin, 2015; Marvin, Tedeschi & Shohamy, 2020) because novel stimuli can be used to activate midbrain dopaminergic structures in both humans and non-human animals (Horvitz, 2000; Wittmann *et al.*, 2007; Laurent, 2008). In gray mouse lemurs (*Microcebus murinus*), the volume of the caudate nucleus is positively correlated with levels of neophilia (Fritz *et al.*, 2020; see Table 2 for glossary) and recent findings in mice show that the activity of glutamic acid decarboxylase 2-expressing (GAD2+) inhibitory neurons in the medial zona incerta (Zlm) increase significantly during explorations of novel objects (Ahmadlou *et al.*, 2021). Yet, it remains unclear to what extent the same neural mechanisms are conserved more widely across phylogeny (Bromberg-Martin & Hikosaka, 2009; Schultz, 2016).

Whilst studies on the neuroscience of curiosity in non-human animals have relied on the use of extrinsic rewards (which are more easily measurable than intrinsic rewards), some recent research has aimed to investigate curiosity without extrinsic rewards. Using longitudinal functional magnetic resonance imaging (fMRI) and dynamic functional connectivity analysis, Tian, Silva & Liu (2021) identified five overlapping brain regions (the cerebellum, the hippocampus, and cortical areas 19DI, 25, and 46D) that activated during curiosity states without food reward in common marmosets (*Callithrix jacchus*), which the authors argued was evidence for 'reward-free curiosity'. Further investigations of how internal rewards shape curious behaviours in animals, as well as examination of the brain regions related to such intrinsic motivations, will reveal to what extent the relationship between curiosity-related neural markers and behavioural measures of curiosity in other species matches that of our own (Gottlieb, Lopes & Oudeyer, 2016).

(2) Curiosity in pre-verbal infants

Children are highly curious, which enables them to learn at an incredibly fast pace in the first years of life (Begus & Southgate, 2018; Kidd & Hayden, 2015). Curiosity in children resembles one proposal by James (see Section II): an instinctual epistemic drive to explore new objects and attend to surprising events. The drive to approach and explore unknown objects is a primary motor for becoming more knowledgeable about their environment. Thus, curiosity in children is understood as a mental state that drives information-seeking behaviours, and which decreases in intensity the more the sought-after information is achieved (Berlyne, 1962, 1966; Loewenstein, 1994). As children acquire language, they can actively ask questions as a way to explore their environment, especially when the events they observe contradict their expectations, which requires them to update their knowledge. While there is strong evidence for epistemic curiosity in children (i.e. a desire for knowledge or intellectual information; Berlyne 1960) it has been less clear whether pre-verbal infants possess the same essential mental capacities. Below we present recent evidence suggesting there may be metacognitive processing of one's knowledge state and exploration targeted towards the unknown during early (i.e. pre-verbal) human development.

(*a*) *Curiosity from a developmental perspective*

Exploration of the environment during early development can maximize knowledge acquisition. Infants display a set of innate biases and preferences for highly informative sources of knowledge. For instance, from birth, infants prefer to look at faces and biologically relevant stimuli as opposed to inanimate objects (Farroni *et al.*, 2005; Turati *et al.*, 2002; Valenza *et al.*, 1996). They also display analogous preferences in the auditory domain for informatively rich sounds, such as infant-directed speech (Cooper & Aslin, 1990; Fernald & Kuhl, 1987). Extant research shows that the characteristics of infants' social environment and their previous knowledge impact their learning and exploration of the environment. When raised by a female primary caregiver infants develop a visual preference for female faces by 3 months of age (Quinn *et al.*, 2002). When raised in an English-speaking context, infants prefer English native speakers, as opposed to non-native speakers (Kinzler, Dupoux & Spelke, 2007). Over the course of the first year, these preferences are tuned to infants' environments and to the most relevant sources of information and are geared at maximizing information gain.

It has long been shown that the pattern of exploration by infants is not random but rather systematically enables them

Table 2. Glossary of terms potentially interlinked with curiosity, or the ways curiosity is measured.

Term	Definition	References	Scientific discipline
Perceptual curiosity	Interest in novel, strange or ambiguous perceptual stimuli that motivates visual and sensory inspection	Berlyne (1954)	Psychology
Epistemic curiosity	The desire for knowledge or intellectual information (applies mainly to humans)	Berlyne (1954)	Psychology
Intrinsic reward	Reward associated with classical task-directed learning, food searching, and environmental variables	Gottlieb *et al.* (2013)	Psychology, neuroscience
Extrinsic reward	Reward associated with internal cognitive variables such as information-seeking, pleasure	Gottlieb *et al.* (2013)	Psychology, neuroscience
Novelty seeking	Enhanced specific recognition, and exploration of novel situations, stimuli, and new experiences	Kelley *et al.* (2004); Redolat *et al.* (2009); Pisula *et al.* (2013)	Psychology, animal cognition, neuroscience
Neophilia	Attraction to a food item, object, or space because it is novel. Attraction to novelty is measured through approaches towards that stimulus.	Greenberg (2003); Brown & Nemes (2008); Griffin *et al.* (2017)	Animal cognition
Neophobia	Avoidance or aversion of novelty, measured through restrained/inhibited behavioural response to a certain stimulus	Reviewed by Greggor *et al.* (2015) and Forss *et al.* (2017)	Animal cognition
Exploration tendency/ exploration	Information acquisition/information gathering regarding objects, space or food items through visual investigation, movement, or object manipulation. The terms are vaguely defined and used broadly without standardization across studies and species.	Massen *et al.* (2013); Forss *et al.* (2017); Rojas-Ferrer *et al.* (2020); Fantz (1964); Baer & Kidd (2022)	Animal cognition, developmental psychology
Exploration	Behaviours driven by an internal motivation to find opportunities optimal for learning	Schillaci *et al.* (2020)	Developmental robotics
Intrinsic motivation	An adaptive function enabling organisms or agents to learn skills and knowledge without the requirement to impact homeostatic needs and/or fitness directly at the time of the learning process	Baldasarre (2011)	Cognitive science
Information gain	Knowledge-based and competence-based intrinsic motivation	Mirolli & Baldassarre (2013)	Developmental robotics
Prediction gain	Exploration guided towards novel or surprising space-states as being less explored	Bellemare *et al.* (2016)	Machine learning
Prediction error	Difference between what is predicted and the actual input. Measure that signals states of surprise, novelty, information gain, learning progress, goals, or tasks with the optimal complexity for learning, and prediction gain	Santucci *et al.* (2020); Schillaci *et al.* (2020); Schmidhuber (1991*b*); Stahl & Feigenson, (2015); Sutton & Barto (2018); Valenzo *et al.* (2022)	Machine learning, computational reinforcement learning, developmental robotics, cognitive sciences

to learn optimally, a concept that has inspired the computational modelling of curiosity (see Section III.3). Infants prefer to attend to the most novel objects (Fantz, 1964) or to objects that are the least predictable or least redundant (Botvinick, Niv & Barto, 2009; Addyman & Mareschal, 2013). They also direct their attention towards stimuli that have optimal levels of complexity: a phenomenon deemed 'the Goldilocks effect'. When pre-verbal infants (7 and 8 months old) were presented with visual stimuli that varied parametrically in complexity, they spent longer looking at stimuli with an intermediate level of complexity compared to stimuli that were either very simple or very complex. This pattern of visual attention was demonstrated with different types of auditory and visual stimuli (Kidd, Piantadosi & Aslin, 2012) and for individual participants (Piantadosi, Jara-Ettinger & Gibson, 2014). The findings are interpreted to mean that infants maximize their learning by implicitly seeking intermediate-level sources of information, which presumably avoids wasting cognitive resources on stimuli that are too easy or too difficult to process.

Previous theoretical frameworks of curiosity have also highlighted other mechanisms that drive early learning, such as the feeling of uncertainty, since it signals an opportunity to learn and the need to close a knowledge gap (Berlyne, 1962; Loewenstein, 1994; Gottlieb *et al.*, 2013). When they are uncertain, children continue to explore objects and seek information (Baer & Kidd, 2022). Pedagogical demonstrations reduce uncertainty because children assume that demonstrators reveal all the relevant aspects of a novel object. After watching a teacher's direct (i.e. to them) or indirect (i.e. to another child) demonstration of how a novel toy squeaks, children are less likely to explore spontaneously other functions of that toy than after witnessing an adult's instrumental action on the same toy (Bonawitz *et al.*, 2012). Consistent with this account, children explore novel objects more broadly when they know that their functions are only partially, as opposed to fully, demonstrated to them by an adult (Gweon *et al.*, 2014). In a word-learning scenario, 3- to 8-year-old children selectively choose items that enable them to reduce uncertainty about novel word meanings (Zettersten & Saffran, 2021). Similarly, younger children between 2 and 5 years of age are more likely to seek help from others when a novel word referent is ambiguous (Hembacher, deMayo & Frank, 2020). Globally, the more aware of their own uncertainty children are, the more likely they are to seek help to close the knowledge gap (Coughlin *et al.*, 2015).

Evaluating uncertainty relies on metacognitive abilities, through a constant assessment and awareness of what is known and what is not known (Goupil & Proust, 2023). Metacognitive skills, however, have long been thought to rely on complex reasoning and the ability to report one's own mental states. Until recently, pre-verbal infants, and even children, were presumed to lack metacognition, and by extension, to lack adult forms of epistemic curiosity. In adults, curiosity and the feeling of uncertainty are most often measured through verbal reports. However, paradigms used in adults are inappropriate for testing children and fail to capture their metacognitive abilities. For example, when using verbal responses children appear unaware of what they know and what they do not know (Taylor, Esbensen & Bennett, 1994). However, when verbal responses are replaced with pictorial scales, preschoolers display awareness of their uncertainty: their level of confidence in their responses reflects their level of accuracy (Lyons & Ghetti, 2011). Recent studies have shown that pre-verbal infants are also aware of gaps in their knowledge. 20-month-old toddlers can monitor their own uncertainty and selectively request help from knowledgeable social partners to avoid making errors (Goupil, Romand-Monnier & Kouider, 2016; Bazhydai, Westermann & Parise, 2020). 12- and 18-month-old infants are also shown actively to track the accuracy of their choices, using implicit behavioural responses and neural measures (Goupil & Kouider, 2016).

Moreover, infants' curiosity is linked to their inner motivation to understand how the world around them works. Recent studies in developmental psychology revealed that infants look longer at surprising events, they systematically explore their surroundings to learn and actively test hypotheses to understand how the world around them functions (Gopnik, Meltzoff & Kuhl, 1999; Bonawitz *et al.*, 2012). For instance, infants look longer at unexpected events, such as a physical object passing through a wall. The proposed explanation for this increase in attention is that surprising events represent opportunities to learn. Decades on infant research consistently showed increased attention following violations of expectations in a variety of domains ranging from physical knowledge (e.g. Baillargeon, 2008), numerical knowledge (e.g. McCrink & Wynn, 2004; Wynn, 1992), probabilistic intuitions (e.g. Téglás *et al.*, 2007), logical reasoning (e.g. Cesana-Arlotti *et al.*, 2018) and theory of mind (e.g. Gergely *et al.*, 1995).

Through unexpected events infants seek and attend to sources of information to test and to refine internal models of the world that allow them to upgrade their beliefs (Griffiths & Tenenbaum, 2007; Leslie, Friedman & German, 2004). Stahl & Feigenson (2015) showed that infants use violations of expectations of their core knowledge as opportunities for learning. They show enhanced exploration of objects that violated expectations (e.g. witnessing a toy going through a wall, violating their expectation of object solidity) and they engage in behaviours aimed at uncovering an explanation for the violation (e.g. banging the toy against a hard surface; Stahl & Feigenson, 2015). When infants are given an explanation for the violation of expectation previously experienced (e.g. they are shown that the wall had a hole) they no longer show increased exploratory behaviour, suggesting that they were searching for an explanation (Perez & Feigenson, 2022). Similarly, 6.5- to 8-month-olds use expectation violations to revise and learn rules about physical knowledge (Wang, Zhang & Baillargeon, 2016). Improbable rather than impossible events, that violate non-core knowledge, also enhance infants' exploratory behaviour. Using traditional violation-of-expectation methods and crawling paradigms, it has been shown that 13-month-olds preferentially attend to and approach sources of unexpected events (Sim & Xu, 2017, 2019). Studies in children also suggest that they look longer following surprising events to understand the source of this unexpected event. For instance, when children are presented with two confounded sources of noise for a novel toy, their exploration is aimed at disambiguating its causal mechanism (Schulz & Bonawitz, 2007).

Although on average infants look longer at violation-of-expectation events, there is great individual variability (Wang, Baillargeon & Brueckner, 2004; Luo & Baillargeon, 2005). Despite this intra-individual variability, a recent study showed that infants' attention to surprising events is quite stable within an individual: looking behaviour at impossible events at 11 months predicts looking behaviours at 17 months, but also parents' ratings of their children's curiosity at age 3 years (Perez & Feigenson, 2021), even when controlling for temperamental differences, vocabulary size or attention to possible events (Lee *et al.*, 2023). A recent study revealed that only certain aspects of infant curiosity (i.e. broad exploration) and of caregiver behaviour (i.e. awe-inducing activities, such as museum visits or nature walks) were related to early attention to surprising events (Lee *et al*., 2023).

Infants not only use their own surprise to learn about unexpected events, but they are also sensitive to others' surprise and use this to modify their beliefs about the world. When 12- to 18-month-old infants witness someone else's surprise to improbable and probable events they show increased looking time to the probable event (Wu & Gweon, 2019). Similarly, children show increased exploration of objects that others were surprised by during play (Wu & Gweon, 2019).

Even before they can speak, infants learn about novel or surprising events in their environment not only by gazing at or manually exploring objects, but often rather than searching for an explanation for themselves, they solicit one from their caregivers. For instance, pre-verbal infants use pointing to request information. Toddlers show superior learning of novel labels and functions of objects they had previously pointed to, suggesting that infant pointing is a sign of their readiness and interest to acquire novel information (Begus & Southgate, 2012; Lucca & Wilbourn, 2018, 2019; Lucca, 2020). When demonstrated the functions of two novel objects, one that the infant pointed to and an ignored one, infants selectively imitated the functions of their preferred objects. This suggests that infants' learning is boosted when their request is satisfied and that their desire to learn facilitates the retention of information (Begus, Gliga & Southgate, 2014). Infants use non-verbal cues actively to request information by selecting knowledgeable social partners, as opposed to ignorant ones (Harris & Lane, 2014; Bashydai *et al*., 2020; Kovacs *et al*., 2014). Once children can speak, their question-asking behaviours become more sophisticated and precise (Ronfard *et al*., 2018). For example, 'why' questions are abundantly used by children to seek further information, to understand how objects function and to test the reliability of the information (Frazier, Gelman & Wellman, 2009).

(*b*) *Neuroscientific research on infants*

Neuroscientists characterize curiosity as an active 'desire' to reduce uncertainty and thereby gather knowledge or understanding about novel or challenging stimuli or situations (Gruber, Gelman & Ranganath, 2014; Silvia, 2008), thus aligning with the information gap theory which posits that a degree of uncertainty can intensify curiosity (Golman & Loewenstein, 2018).

Several factors can evoke curiosity and both intrinsic and extrinsic rewards play important roles in promoting and maintaining high levels of curiosity in early life. Recent studies have shown that intrinsic rewards, such as the satisfaction of solving a problem or completing a task, can activate brain regions related to high curiosity states in human infants and children. For example, exposure to strong and repetitive auditory stimuli in 5–7-month-old infants results in heightened activity in the temporal lobe, which is linked to attention, memory, and ultimately, curiosity (Emberson *et al*., 2017). Furthermore, the prefrontal cortex is crucial for attentional control, exploration, and processing of sensory information in infants and this brain region has been associated with perceptual curiosity, as it undergoes significant development during the early years of life (Gruber & Fandakova, 2021). 8-month-old babies who were presented with novel stimuli showed greater activity in the prefrontal cortex, which also suggests behavioural support for this assumption (Werchan *et al*., 2016). Moreover, 4-month-old babies with strong reactions to novel and unfamiliar stimuli showed an increase in the thickness of their cortex, specifically in the region of the right ventromedial prefrontal cortex (Schwartz *et al*., 2010). Another study that used functional near-infrared spectroscopy (fNIRS) to measure brain activity found that 3-month-old babies' bilateral prefrontal regions show highly significant activation towards a novel stimulus (Nakano *et al*., 2009). Taken together, these results suggest that novel and uncertain stimuli intensify curiosity states and the specific brain region of the prefrontal cortex represents a neural marker of curiosity in human infants.

Other findings suggest the anterior cingulate cortex (ACC), another brain region known to be involved in cognitive control and decision-making, is activated during exploration of novel stimuli, but not by familiarity exploration (Bush, Luu & Posner, 2000). Also, the hippocampus, which is involved in memory formation and retrieval, can detect and respond to novel stimuli (Langston *et al*., 2010; Kidd & Hayden, 2015). The hippocampus and the neighbouring areas around the medial temporal lobe have been linked to novelty preference, which in turn is believed to be crucial for visual attention and object recognition memory necessary for curiosity during infancy (Reynolds, 2015). Thus, these studies imply that the ACC and hippocampus potentially also represent neural markers of curiosity. As children grow older, the amygdala, a region involved in processing emotions and novelty detection, has been associated with curiosity (Jepma *et al*., 2012) and activity in the dopaminergic reward system, including the ventral striatum and the prefrontal cortex (Kidd & Hayden, 2015; De Pisapia, Bacci & Melcher, 2016).

(3) Computational modelling of curiosity in artificial systems

The capability to learn new information and skills autonomously and continuously is strongly related to curiosity. Therefore, the computational modelling of curiosity-related behaviours has evoked particular interest in artificial intelligence (Baldassarre & Mirolli, 2013), as well as allied fields such as computational reinforcement learning (Sutton & Barto, 2018), deep reinforcement learning (Kulkarni *et al*., 2016), cognitive robotics (Schillaci, Ciria & Lara, 2020), and developmental robotics (Oudeyer, Kaplan & Hafner, 2007), among others. There are multiple approaches to building artificial systems with the capability autonomously to seek novel situations in the environment and continuously to acquire new information and skills. The computational modelling of intrinsic motivation has not only been used to permit exploration and goal-directed learning in artificial systems (Santucci, Baldassare & Mirolli, 2014), it has also been used for the autonomous selection of goals or tasks (Baranes & Oudeyer, 2013; Santucci, Baldassare & Cartoni, 2019; Schillaci *et al.*, 2020).

Within the literature on computational modelling of curiosity, the mechanism behind the capability for autonomous open-ended learning is traditionally referred to as intrinsic motivation. However, given that intrinsic motivation is closely related to curiosity-related behaviours, the terms 'intrinsic motivation', and 'curiosity' are often used interchangeably. Additionally, the nature of these definitions tends to be influenced by the discipline that a specific study took as inspiration. This is particularly problematic as there is no consensus on a definition in a particular research field and even less across research fields. Thus, in different computational approaches, the term 'intrinsic motivation' has been used while disregarding what it means in studies of psychology (for example, see Oudeyer & Kaplan, 2009).

(*a*) *Definitions and typologies in computational modelling of curiosity*

In general, artificial systems that can autonomously explore and behave to learn and acquire knowledge are considered to have artificial curiosity (Schmidhuber, 1991*a*,*b*). Schillaci *et al.* (2020) proposed that intrinsic motivation exists when a system autonomously seeks new experiences and generates exploratory behaviours for learning by self-generating goals depending on its current knowledge and capabilities. More specifically related to curiosity, Oudeyer *et al.* (2007), developed what they called an 'Intelligent Adaptive Curiosity' (IAC) system, inspired by Berlyne's (1960) original definitions of intrinsic motivation in animals. The system is intelligent because it avoids situations that are either too predictable or too unpredictable, thus learning from situations with optimal complexity (see similarities with the Goldilocks effect, Section III.2.*a*). The system is adaptive because the novel situations it is attracted towards change as a function of its learning progress. And the system has intrinsic motivation because the learning progress, kept at its maximal level, actively drives the system towards novel situations.

In both psychological and computational models of intrinsic motivation, the same relevant distinction has been made between 'knowledge-based' and 'competence-based' intrinsic motivation (Mirolli & Baldassarre, 2013). Knowledge-based intrinsic motivation is intended for accumulating knowledge based on the capacity of the system to model itself and its environment to predict the consequences of its actions; in other words what Goupil & Proust (2023) describe as foundations for metacognition. On the contrary, competence-based intrinsic motivation is for acquiring skills based on what the system can do by means of using predictions to obtain a measure of its competence to produce effective interactions with the environment.

Along this same line of thought, Oudeyer & Kaplan (2009) set the ground for an operational study of intrinsic motivation by establishing a typology of different computational approaches and distinguishing between knowledge-based and competence-based intrinsic motivation. Knowledge-based models of intrinsic motivation are classified into two sub-approaches related to the way knowledge and expectations are represented: first, information theoretic and distributional models which include uncertainty motivation, information gain motivation, distributional surprise motivation, and distributional familiarity motivation. Secondly, predictive models include predictive novelty motivation, intermediate level of novelty motivation, learning progress motivation, predictive surprise motivation, and predictive familiarity motivation. Competence-based models of intrinsic motivation are scarce but still some classification has been made to consider different approaches: maximizing incompetence motivation, maximizing competence progress or flow motivation, and maximizing competence.

Despite the complexity behind finding a consensus on a definition of curiosity and intrinsic motivation in computational modelling, it is still possible to highlight an agreement. Here we suggest that, in the computational modelling of curiosity, intrinsic motivation and exploration are two sides of the same coin. Curious artificial systems need to have an internal drive to explore and learn. This internal drive is not directly related to extrinsic rewards; instead, it has its roots in acquiring either knowledge or competence (Mirolli & Baldassarre, 2013). This drive can be understood as an attraction to novelty, and the capability to experience both curiosity and pleasant surprise by discovering. In the literature of the computational modelling of curiosity, this internal drive is commonly related to the terms 'continuous learning' or 'lifelong learning' (Lungarella *et al.*, 2003; Lesort *et al.*, 2020; De Lange *et al.*, 2021). Lifelong learning can be achieved as a direct consequence of being intrinsically motivated to explore new space-states. Importantly, the capability of computational modelling to explore and prefer novel situations for learning is strongly based on prediction-based mechanisms. States of surprise elicited by novel situations can be directly measured by means of the amount of prediction error (i.e. the difference between what is predicted and the actual input).

(*b*) *Prediction error: the gold standard measure*

Prediction error is an extremely useful measure to quantify novelty and learning progress, the idea being that curiosity-related behaviours can be summarized as the exploration of what is surprising to maximize learning progress. Thus, being able to quantify prediction error is the gold standard measure behind computational modelling of intrinsic motivation and exploratory-related behaviours in artificial systems. Exploring novel space-states for information gain requires the ability to measure how much the encountered information differs from what is already learned and accurately predicted. Therefore, terms related to prediction error such as novelty, informativeness, and surprise, are commonly used as a measure of information gain when intrinsic motivation is modelled, and prediction gain when exploratory behaviours are modelled.

(*c*) *Computational approaches to measure curiosity*

Curiosity-driven learning is a promising framework for developing autonomous lifelong learning in machines and artificial embodied systems in developmental robotics (Santucci *et al*., 2020). When it refers to (non-embodied, non-situated) machines, the most widely used tool for curiosity-driven learning is computational reinforcement learning (CRL). This is likely the case because this approach provides learning algorithms that can be applied in a wide range of tasks and scenarios that require knowledge-based or competence-based intrinsic motivation. When it refers to artificial embodied systems within the developmental robotics field, there are a wide variety of tools and methods, including neural networks, artificial evolution, and even CRL. In developmental robotics, curiosity-driven learning has generated increasing interest due to its crucial mechanism for ontogeny (Oudeyer *et al*., 2007).

Embodied and non-embodied methods share an interest in curiosity-driven learning and the fact that prediction error must be quantified to (*i*) measure novelty, (*ii*) determine the optimal space-states/goals to explore, and (*iii*) measure the learning progress towards acquiring new knowledge or skill. Among the remaining salient challenges in the computational modelling of curiosity are: the autonomous selection of actions that will lead to learning and that are useful for solving tasks; autonomous goal selection and the related actions for achieving it; autonomous exploration of space-states; and the exploitation and exploration dilemma (Santucci *et al*., 2020). Additionally, a well-known challenge related to learning multiple tasks is that of 'catastrophic forgetting', which means how new knowledge interferes with what has already been learned (Parisi *et al*., 2018; Xiong *et al*., 2021).

Finally, one of the most important remaining challenges is the problem of relevance and decision-making between competing internal and external drives and goals in each situation. In biological agents, innate phylogenetically acquired knowledge, physiological needs, and emotions are crucial for decision-making. Although there are some theoretical proposals on how to model these factors in artificial systems (Valenzo *et al*., 2022), it is still an open question.

(i) Non-embodied machines. For non-situated machines, the most common computational tool is CRL, a framework that borrows observations from behavioural psychology, particularly from operant conditioning research. Thorndike (1911) described how biological agents are affected by new stimuli and situations associated with responses which are reinforced by positive and negative consequences. The rewards are external and specific to a particular environment and context. Thus, by means of reinforcement learning, agents learn what to do through trial and error, and how to map situations aligning with actions to maximize the reward signal through interactions with the environment. CRL is focused on goal-directed learning where the most rewarding actions must be discovered in uncertain environments (Sutton & Barto, 2018).

Traditionally, curiosity has been modelled in artificial systems with the assumption that novelty-based exploration is intrinsically rewarding. CRL has been widely used to build algorithms that incorporate internal reward functions to drive exploratory behaviours and novelty preference (Barto, 2013). Internal rewards can be understood as a mathematical value associated with learning or with the acquisition of a skill (Barto, 2013). With this view, intrinsic motivation is related to those task-independent internal rewards, but at the same time, the artificial system needs autonomously to seek them to be able to solve the task (Mirolli & Baldassarre, 2013). Schmidhuber (1991*a*,*b*) was apparently the first to suggest that curiosity is interlinked with a reward that is proportional to the predictability of the task in question, and further curiosity depends on the expected learning progress associated with a particular action. The CRL algorithm implemented by Schmidhuber (1991*b*) learned to predict the next state, given the current state, and the execution of an action related to the task at hand. This algorithm was designed to select those actions, the consequences of which were hard to predict, but at the same time signalled learning and intrinsic rewards for the system. The intrinsic rewards were complemented with extrinsic rewards related to the performance accomplished in the task. This CRL algorithm was able to learn autonomously to improve its own model by exploring unpredictable action states, as well as to maximize external rewards related to the task. CRL learning algorithms are developed with the aim to maximize the sum of future external and internal rewards (Sutton & Barto, 2018).

The use of intrinsic rewards is a powerful tool to drive learning in artificial systems, even without the use of any external reward (Pathak *et al*., 2017; Burda *et al*., 2018). For example, Burda *et al*. (2018) designed a CRL algorithm based solely on intrinsic rewards to compare its performance against CRL algorithms based on external rewards. The CRL algorithms were tested across 54 standard benchmark environments, including the 'Atari game suite'. Their results show a surprisingly high performance of the CRL algorithm on intrinsic rewards in comparison to the manually designed extrinsic rewards of many game environments. Besides internal rewards, which are strongly related to intrinsic motivation and information gain, there are other prediction-based mechanisms for exploration that foster learning. For example, the frequency or count-based exploration of space-states is used as a measure of prediction gain by exploration (Bellemare *et al*., 2016). Thus, exploration can be guided towards those novel or surprising space-states that have been less explored. The concept of prediction gain for exploration can be related to Sutton's (1991) concept of 'exploration bonus' rewards. These are rewards an artificial agent receives for visiting states in proportion to the temporal interval since it previously visited that state. Interestingly, Bellemare *et al.* (2016) designed a novel algorithm that used both predictions gain for exploration, and information gain for intrinsic motivation. This algorithm was applied to 2600 Atari games and scored higher than previously reported scores.

Finally, a CRL goal-seeking system must deal with the exploitation/exploration dilemma. This describes the choice between exploiting what it is already learned to obtain an expected external reward, or being intrinsically motivated to explore and learn new information or behaviours that could bring favourable future outcomes such as external rewards (Sutton & Barto, 2018; for comparison with animals in risky environments, see Section III.1.*d*). Competing choices are omnipresent in the course of decision-making and learning. Thus, a goal-seeking system needs to be equipped with a mechanism to determine if a situation is better suited for exploitation or exploration. It could be that intrinsically motivated behaviour serves to generate a repertoire of skills that are useful for extrinsically motivated tasks (Barto & Simsek, 2005). With this view, it is important to define not only the specific environmental context but also an agent's internal context (Valenzo *et al.*, 2022; Barto & Simsek, 2005). This definition will create the basis for making richer forms of understanding intrinsic rewards (Barto & Simsek, 2005).

(ii) Embodied machines. Until this point, we have focused on the 'cognitive' mechanisms possessed by an artificial system; in other words, the 'brain' it requires to be curious. However, an artificial system also needs a *body* to interact with the environment and gradually acquire knowledge and action possibilities (Pfeifer & Iida, 2004). Embodied artificial agents need autonomously to seek and cope with novel situations to learn from these experiences and constantly increase their behavioural complexity. Different research fields such as psychology, neuroscience, developmental psychology, and animal cognition (e.g. Berlyne, 1960, 1966; Deci & Ryan, 1985; Dayan & Balleine, 2002; White, 1959) have inspired the embodiment of intrinsically motivated open-ended learning artificial agents.

Some milestones of embodiment include the approach of Oudeyer *et al.* (2007), where an artificial agent was able to develop, in an open-ended manner, an IAC system that used CRL for internal rewards, as well as other computational tools to measure prediction error and learning progress. The IAC system maximizes learning progress by avoiding situations that are too predictable or too unpredictable. The learning progress motivation was coupled with a region-splitting mechanism of behaviours and sensorimotor categories, which was used to measure prediction error by comparing situations in a 'regional' manner. Each region had an associated error allowing the system to select the region to explore which had the optimal amount of prediction error. A self-organization of a developmental trajectory to learn new possibilities of action was achieved by maximizing internal rewards when a situation previously not mastered becomes mastered with the optimal time and effort.

Inspired by Forestier *et al.* (2022), Schillaci *et al.* (2020) presented an intrinsic motivation architecture capable of generating autonomous exploratory and curiosity-related behaviours in an artificial agent. Importantly, the artificial agent was able to self-generate and select goals but was constrained to those that generated reducible prediction error. For this architecture, the underlying mechanism was a sensitivity to performance and its associated artificial emotions which were grounded on a multilevel monitoring of prediction error dynamics. This was considered a type of self-regulating mechanism associated with artificial emotions. If the system detected that prediction error was minimized when pursuing a goal, a positive 'emotion' was experienced, and the system was intrinsically motivated to continue the goal until there was no more error to reduce. On the contrary, when prediction error was not reduced, that is, when the system monitored that it was failing or not improving in pursuing a goal, a negative emotion was experienced. To avoid 'frustration', the system tried to improve a few more cycles, but if prediction error kept not being reduced, the system was intrinsically motivated to abandon the goal and to search for a new goal with lower complexity. The goals were autonomously generated and selected according to their prediction error dynamics. Selected goals had the optimal amount of reducible prediction error. This strategy for goal selection provides a solution for balancing exploitation and exploration. This architecture presents a baseline for further understanding of the relevance of monitoring prediction error dynamics for the computational modelling of intrinsic motivation together with artificial emotions.

Recently, there has been a convergence between the approaches of developmental robotics and deep reinforcement learning methods for tracking the problem of intrinsic motivation and lifelong learning. This new domain of study is called developmental machine learning. Colas *et al.* (2020) proposed a typology of the methods to train artificial agents to generate and pursue their own goals based on developmental machine learning. This typology considers Intrinsically Motivated Goal Exploration Processes (IMGEPs), with Goal-Conditioned (GC) Reinforcement Learning algorithms. Under this view, artificial agents equipped with a GC-IMGEPs system will autonomously represent their goals, generate them, and will be intrinsically motivated to learn to achieve the goal while measuring their own progress. In the proposed typology, different types of goal representation associated with a specific goal-conditioned reward function were identified. Additionally, in typology the reward functions (i.e. giving a positive reward) are explained considering which type of goal representation is selected for measuring progress.

IV. DISCUSSION

(1) Disciplinary overlaps and their implication for current views on curiosity

In this review, we sought to shine a spotlight on curiosity research on non-linguistic systems: non-human animals, pre-verbal infants, and artificial agents. We were interested to reveal to what extent these systems differ or overlap in their assessments of curiosity, and how they may move the study of curiosity away from the more dominant paradigms in human psychology. This review has revealed three main findings. (*i*) Across all 'intelligent systems' curiosity can be sparked by surprise and uncertainty and plays a central role in optimizing learning processes in the presence of novel stimuli and situations. (*ii*) Across systems, the level of uncertainty needs to be optimal to result in curiosity: too large a gap may cause anxiety/retreat (expressed through neophobia in animals), and too short a gap may not be sufficient to trigger the need for information-seeking behaviours (Day, 1982). (*iii*) The information gain itself (resulting from exploration) is considered rewarding for the agent.

In Table 1, we summarize how different scientific disciplines have defined curiosity. As expected, in systems where one cannot use self-assessments nor infer a state of the mind, definitions are broad (arguably ambiguous) but with the commonality of describing a motivation to aid learning processes. Interestingly, within animal cognition, the criterion for curiosity is somewhat stricter (information-seeking or exploratory behaviours must fall outside general survival activities and/or cannot have any immediate reward to the exploring individual) (Byrne, 2013; Wang & Hayden, 2019), whilst for other disciplines the actual explorative action is driven by information being the reward (Loewenstein, 1994; Bromberg-Martin & Hikosaka, 2009; Zhai *et al.*, 2019).

In computational cognition, the inspiration for prediction error calculations derives from how human infants attend to stimuli when exploring their environments. For example, infants prefer to attend to those stimuli that are neither too complex nor too simple, maintaining an intermediate rate of information complexity to be able to learn incrementally (Kidd *et al.*, 2012). In line with the theory behind the U-shaped curve optimizing learning progress (Kidd & Hayden, 2015), the concept of optimal complexity in computational cognition provides a logical solution to the problem of what is relevant to learn and what must be ignored because it is already learned (Stahl & Feigenson, 2015). Thus, in the same way that computational models use optimal levels of complexity to facilitate the balance between exploration and exploitation, such models also offer a possibility to evaluate whether a similar learning-optimization strategy is applicable for both neural networks and artificial ones. To what extent other non-human species adjust novelty interest and learning progress according to similar reference points is yet for animal cognition scientists to uncover.

Researchers in the field of animal cognition have been cautious when classifying a behaviour as curiosity because it needs to be sufficiently differentiated from other concepts like neophilia/neophobia, and there is also an ingrained concern about anthropomorphism and violating Morgan's Canon. By contrast, child psychologists seem more freely able to infer that curiosity is the driver behind exploration and learning in babies, even though many of the behavioural indicators used to do so are the same for animals (Section II).

In Table 2 we list different terminology used across disciplines that interlink with curiosity. Across disciplines, multiple terms describe the initial step of recognizing/seeking new information, which is necessary to guide an organism (or agent) towards curiosity-driven learning: 'perceptual curiosity' (psychology), 'novelty-seeking' (psychology, animal cognition, neuroscience), 'neophilia' (animal cognition), 'exploration' (animal cognition, developmental psychology, developmental robotics) (Table 2).

According to the literature, the distinction between what is information and what is knowledge colours how curiosity is viewed. As we have seen, both biological and artificial agents require an internal mechanism for information-seeking in order to adapt to their environments. Such internal motivation is the basic biological mechanism underlying exploratory behaviours, combining internal states (such as an organism's metabolism, hunger state or level of uncertainty) with encounters with external stimuli (such as food presence or novel stimulus) (Pisula, Turlejski & Charles, 2013). However, true curiosity-based exploration has been argued to require an additional element; the assessment of newness followed by a pursued motivation to gain more knowledge about the discovered available new information (Pisula, 2020).

Beyond humans (who can self-report), curiosity is a contentious phenomenon to quantify because it is difficult to measure meta-cognition in non-linguistic beings. Some categorize curiosity with affective states or epistemic emotions as strictly 'first order', just like feelings of fear, and thus do not incorporate a monitoring function. In this view, non-human animals and infants engage in explorative behaviours without using or having the concept of knowledge (Carruthers, 2018). However, recently an intriguing contra-proposal was made by Goupil & Proust (2023), who argue that curiosity is a special type of 'metacognitive feeling' and represents an affective state resulting from an agent monitoring the success or failure of its own cognitive actions, which in the case of curiosity would be identifying and recognizing potential new information and acting thereupon. In fact, Goupil & Proust (2023) suggest that developing babies and animals engaging in curious information-seeking represents rudimentary evidence for metacognitive competence. Thus, seeking and/or recognizing new information may be a pre-condition for true knowledge gain of a certain stimulus/situation. As we have seen, human infants show the same pre-condition of curiosity from their first months of life. Their behavioural explorations, requests for help and evaluations of their own and others' knowledge become more sophisticated across the course of their development. By documenting cases across non-linguistic systems showing increased interest in novelty, exploration of new stimuli and the balance of such explorative acts depending on external factors influencing assessment, our review supports the provocative suggestion made by Goupil & Proust (2023) of curiosity representing a fundamental meta-cognitive trait, which likely stretches (at least in some forms) beyond human adults.

(2) Do we need a dichotomic view of curiosity?

An early (19th century) division of curiosity into two distinct types (biological and uniquely human/requiring language; James, 1890) left a long-lasting impression on its scientific study. Whilst many scholars have acknowledged the existence of curiosity in animals and its biological function as a mechanism necessary for learning, others have instead argued that such explorative behaviour represents a clear-cut distinct phenomenon to what James referred to as 'scientific curiosity', which he described as the human-like desire to fill a knowledge gap (James, 1890). In the current literature there are two other major divisions of curiosity which have prevented straightforward definition: (*i*) a drive to seek out information, and (*ii*) an underlying internal motivation to learn something new (Marvin *et al.*, 2020). By reviewing the curiosity literature extending beyond adult humans, we have highlighted that all intelligent systems, whether human babies (unable to assess their own knowledge status), non-human animals or artificial agents, possess the ability to seek and recognize new information, and that this ability is facilitated by intrinsic motivation. Thus, one can start to question to what extent the traditional dichotomic view is a reflection of the available (or in many cases non-available) tools to measure internal motivations in non-linguistic beings, rather than clear evidence for human uniqueness.

One way to bridge the gap between these dichotomous divisions would be to address both views within the same model system. While somewhat time consuming, yet highly interesting, one could apply a longitudinal approach in humans to investigate the relationship between behavioural measures and later-life self-assessments within individuals over time. Behavioural measures from animal cognition and developmental psychology could evaluate early curious tendencies in babies, which can be complemented with neuroscientific approaches to detect signals of neurological markers of curiosity at different developmental stages. The same individual's behaviour and self-evaluation can be followed up later in life to evaluate the inter-individual agreement across methods and life stages.

(3) Transdisciplinary future approaches

Whilst behavioural measures of exploration represent what is 'observable' about curiosity across animals, infants, and artificial agents, capturing the essence of the trait in comparative work remains a challenge and may require a combination of paradigms. One obvious overlap between developmental psychology and animal cognition is the observation of explorative behaviour. Quantifying interest towards various objects and problem-solving can be achieved using multiple behavioural indicators, such as spatially approaching/retreating, gaze direction and fields of attention, attention spans, types of object manipulation, gesturing, and persistence. Such multi-component measures of exploration are already established in great ape studies and the umbrella term 'curiosity' has been used to combine underlying correlated exploratory measures (Damerius *et al.*, 2017*b*; Forss & Willems, 2022). We suggest that a model of curiosity should include multiple components, like exploration, knowledge awareness, and violation of expectation that can be comparatively studied in non-linguistic beings. We currently know very little about how such traits may be intercorrelated in animals and human infants, but this knowledge is crucial to understanding the building blocks of curiosity and its evolutionary history. Despite their intimate relationship in understanding the part curiosity plays in the process of learning, and the fact that these two scientific fields face similar restrictions on the use of language-based methods, surprisingly few direct empirical comparative studies exist between human toddlers and our closest living relatives (but see Herrmann *et al.*, 2011). The comparative interest between these disciplines has been larger for the related concept of play behaviour (Pellegrini & Smith, 2005). Here we suggest that suitable experimental designs that examine curiosity using behavioural measures open the intriguing possibility to quantify aspects of curiosity not only in non-human animals and preverbal infants, who are too young for self-reported measures on internal states, but also to some extent in artificial intelligences, whose progress also depends on curiosity-driven learning (Baldassarre & Mirolli, 2013; Colas *et al.*, 2020; Oudeyer & Kaplan, 2009; Schmidhuber, 1991*a*,*b*; Sutton & Barto, 2018).

To this end, new methods such as measuring theta brain wave oscillations [as an indicator of active learning see Begus & Southgate (2018) and Begus & Bonawiz (2020)] could help to identify neural correlates of curiosity across a phylogeny (e.g. in human infants and great apes). A more practical method that has already been validated for non-human use is non-invasive eye-tracking (Kano & Tamonaga, 2009; Karl *et al.*, 2020; Lewis & Krupenye, 2022). The only shortcoming of such comparative paradigms is that they require extensive training in non-human animals, and as such can only be applied in highly controlled laboratory or research centre conditions; this requires extensive exposure to humans and thus animals may become partly enculturated through their experiences. Given the reported differences in curiosity between wild and captive settings (Section III.1.*d*), such methods will perhaps have limited ecological/biological validity.

Where technological tools may fall short in their translation to non-human animals, we still argue strongly for intensified dialogue between developmental psychologists and animal behaviour researchers. As discussed herein, human infants use pointing gestures as a request for knowledge (Kita, 2003; Tommasello, Carpenter & Liszkowski, 2007), and so the desire to 'know more' is present early in human development. When learning their diet, great ape infants watch food items that are rare in their mother's diet for longer (Jaeggi *et al.*, 2010; Schuppli *et al.*, 2016), thus indicating an ability to recognize and seize a novel learning opportunity. Moreover, ape infants also beg more frequently for food items from their mothers that are harder to process, which has been suggested as a request for information on how to process such items rather than a sole need for nutrition (Jaeggi, Van Noordwijk & Van Schaik, 2008). These isolated examples point towards phylogenetic commonalities worthy of further investigation.

If curiosity and its functions are approached in similar ways to the scientific study of intelligence, we may consider taking a ‘modular’ or ‘domain’ approach where we measure multiple interconnected underlying behaviours (surprise and/or uncertainty-evoked reactions, novelty exploration, violation of expectations, etc.) that combine to produce an organism’s curiosity state. And in the continued spirit of taking inspiration from biological systems, we recommend that future research on the functions of curiosity is framed around Tinbergen’s four questions (survival value, ontogeny, evolution, and causation; Tinbergen, 1963). This will ensure that curiosity research remains open and avoids compartmentalization. In particular, we encourage more neuroscientific research, which can make significant contributions to our understanding of underlying causative mechanisms like needs, and links to adaptive functions such as enhanced memory capacity. Finally, since curiosity is a function of lived experience, we urge more research examining how curiosity changes across an agent’s lifetime, from birth to death.

V. CONCLUSIONS

(1) Research approaches on non-linguistic agents (where one cannot infer a state of the mind or use self-assessments) collectively define curiosity broadly as ‘a motivation to aid learning processes’.
(2) Throughout this review, it is clear that reducing uncertainty is a common prediction of when and how curiosity is expressed across systems.
(3) In all disciplines (developmental psychology, animal cognition, neuroscience, and computational cognition) we found approaches that are united in the view and methodology that curiosity can be sparked by surprise and uncertainty.
(4) Our review supports the provocative suggestion made by Goupil & Proust (2023) that curiosity represents a fundamental meta-cognitive trait that potentially stretches (at least in some forms) beyond human adults.
(5) We welcome and outline intradisciplinary exchange not only on theoretical levels but also regarding methodologies.
(6) We suggest that a model of curiosity should include multiple components, like exploration, knowledge awareness, and violation of expectation that can be studied comparatively also in non-linguistic beings.

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VII. AUTHOR CONTRIBUTIONS

This review is a product of a Diverse Intelligences Summer Institute run by UCLA followed by a transdisciplinary workshop, conceptualized, and organized by S. F. together with the Collegium Helveticum, ETH Zurich. The introduction and discussion were written by S. F. and F. C. Disciplinary sections and tables of definitions and terminology were led by the following authors: historical overview – D. H.; developmental psychology – C.-I. G.; animal cognition – S. F. and F. C.; neuroscience – S. L.; computational modelling – A. C.

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