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Review

The making of number: from content to representation

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Despite their importance to human thought, the origins of numerical abilities remain debated. Numerical quantity is a property of physical objects and events, and both humans and many animals show an innate sensitivity to this numerical content. Yet how this content is represented is a separate question: it may be encoded nonsymbolically by an innate estimation system or symbolically through culturally developed formats, such as numeral notations and number words. Distinguishing content from representational format reconciles the views that numbers are innate (nativism), learned (empiricism), or constructed (emergentism). Converging evidence from developmental psychology, comparative cognition, neuroscience, and computation suggests that number is dynamically coconstructed by biological predispositions and cultural practices, a framework that generalizes to other domains of human cognition, such as geometry and language.

Highlights

Numerical cognition requires a distinction between discovered content (objective numerical quantity) and invented format (symbolic representation).

From a nativist perspective, humans and many animals are born with an approximate number system that gives an intuitive sense of quantity.

From an empiricist view, exact numbers and arithmetic are cultural inventions, learned through language, education, and symbolic tools.

An emergentist view emphasizes that numerical abilities are shaped by the ongoing interaction between innate sense and cultural experience.

Evidence from developmental psychology, comparative cognition, neuroscience, and computational modeling shows that number—like geometry and language—is dynamically coconstructed through the interaction of biological predispositions and cultural practices.

Numbers between discovery and invention

Numbers are fundamental to science, technology, and everyday reasoning, helping us measure, compare, and make sense of quantities in the world. Yet a foundational question remains: what kind of entities are numbers? Are numbers discovered features of the world or invented constructs of the human mind? This question is not merely philosophical; it shapes empirical research in psychology, anthropology, neuroscience, and artificial intelligence (AI). Competing frameworks offer different answers (Box 1). Nativist theories claim that numerical competence is biologically endowed, rooted in an evolutionarily ancient faculty. Empiricist perspectives emphasize that formal number concepts and arithmetic precision are cultural inventions, dependent on language, education, and social practices. Emergentist views bridge these positions, proposing that numerical cognition arises through interaction between innate predispositions and experience-dependent learning.

My central claim is that the nativist–empiricist debate hinges on a hidden conflation between 'numerical content' and the 'representational formats' used to encode number (Figure 1). Distinguishing these levels resolves apparent theoretical conflicts and allows findings from development, anthropology, animal cognition, neuroscience, and computational modeling—often seen as incompatible—to be integrated. This unified framework highlights how innate sensitivities and cultural practices jointly shape numerical cognition.

Numerical content refers to what is represented: the objective property of numerical quantity itself. Following Frege [2], I hold that the number of elements in a collection is an objective feature of the world, independent of our beliefs or representational systems. Numerical quantity is a mind-independent structural property of sets, comparable to physical properties such as mass or spatial extent. A flock of five birds has five members, whether or not anyone perceives or names them. Organisms may or may not detect this property, but its physical instantiation

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Box 1. Nativism, empiricism, and emergentism

Nativism, the view that the mind is endowed with certain forms of knowledge, can be traced back to Plato (Meno, 81c–d), who argued that learning is the recollection of innate truths. Later, René Descartes proposed the existence of innate ideas, and Immanuel Kant contended that space and time are *a priori* intuitions—necessary conditions for experience. Building on this tradition, nativist accounts of numerical cognition propose that numerical competence is innate, biologically constrained, and embedded in the brain's core architecture. Humans are thought to possess an evolved 'number sense', reflecting genetically specified, domain-specific mechanisms. Accordingly, nativist theories predict that behavioral and neural signatures of numerosity should be detectable early in development, even at birth, and generalize across species.

Empiricism, in contrast, holds that the mind begins as a *tabula rasa*, devoid of innate content, so that all knowledge arises from experience. This perspective traces back to Aristotle and was later developed by John Locke and David Hume. From this view, numerical abilities emerge through learning and interaction with the environment, with cultural and educational experiences shaping the structure and precision of number systems. Empiricist accounts therefore predict that numerical sensitivity is gradually acquired and refined, depending strongly on experience and context.

Emergentism traces its philosophical roots to John Stuart Mill, primarily an empiricist, who argued that complex mental phenomena arise from simpler experiences but cannot be fully reduced to them, and to George Henry Lewes, who first used the term 'emergent' systematically. Emergentist theories propose that numerical cognition develops through interactions among perceptual and cognitive systems—such as quantity perception, spatial processing, attention, and language—together with innate architectural biases and experiential learning. Closely aligned with cognitive constructivist approaches [1], these accounts view children as actively constructing numerical concepts from simpler components. In this view, numerical competence emerges dynamically from the interplay of biology, learning, and culture.

Collectively, the nativist, empiricist, and emergentist perspectives provide a structured framework for understanding the origins of numerical cognition, generating distinct, testable predictions explored in the following sections.

does not depend on perception. In contrast, 'representational format' refers to how that content is encoded, whether through approximate, nonsymbolic systems or precise, symbolic notation, such as numerals or number words. Framing the problem this way suggests that numerical content is discovered, reflecting evolutionary and perceptual realities, aligned with **mathematical realism** (see Glossary) [3]. In contrast, its symbolic format is culturally invented, reflecting **mathematical anti-realism** [4].

This distinction helps reconcile seemingly contradictory findings. The **approximate number system (ANS)** provides an innate, species-general sensitivity to numerical content. By contrast, the precision and combinatorial structure of formal mathematics depend on symbolic formats that are cultural inventions. Crucially, the human brain is uniquely equipped to learn and internalize open-ended **symbol systems**, enabling number words, numerals, and place-value notation to integrate with neural circuits for quantity [5–7]. Numerical cognition thus reflects co-construction: evolved representations of content are progressively reformatted through culturally created symbolic tools.

In this review, I integrate evidence across three complementary levels of analysis. First, discovered content encompasses behavioral, neurobiological, and comparative findings that reveal innate representations of numerical quantity (numerosity). Second, invented format highlights developmental, cross-cultural, and neurocognitive evidence, showing how exact numbers emerge through symbolic and cultural construction. Finally, the level of co-construction and emergence captures how these innate sensitivities and learned symbols interact dynamically, producing the full spectrum of human numerical competence.

I conclude that numerical cognition exemplifies a broader principle in cognitive science: **representational co-construction**, in which biological predispositions and cultural practices jointly shape how we perceive and manipulate numbers. Distinguishing innate numerical content from culturally invented symbolic formats provides a unified framework for understanding the

Glossary

Approximate number system (ANS): a cognitive system that allows humans and some animals to nonsymbolically estimate and compare numerical quantities without counting. Estimation is ratio dependent and follows the Weber–Fechner law.
Bayesian models: computational frameworks describing how agents integrate prior knowledge and new evidence—weighted by their uncertainty—to make probabilistic inferences and guide decision-making.
Cardinality: the quantity of items in a set (how many there are).
Deep neural networks (DNNs): a type of deep learning model consisting of multiple layers of interconnected nodes ('neurons') that transform inputs into outputs, enabling the system to automatically learn hierarchical patterns and representations from data.
Developmental dyscalculia: a neurodevelopmental disorder characterized by persistent difficulties in understanding numbers, learning arithmetic facts, and performing calculations.
Emergentism: a cognitive science theory suggesting that complex abilities, like language or numerical skills, develop from the dynamic interaction of simpler cognitive, neural, and environmental factors.
Empiricism: a theory in cognitive science and philosophy which holds that knowledge and understanding are primarily derived from sensory experience.
Estrangement hypothesis: the assumption that symbolic numbers eventually become decoupled from ANS representations, relying on specialized, distinct neural populations for exact arithmetic.
Mapping hypothesis: the hypothesis that symbolic numbers are initially learned by mapping them onto pre-existing ANS.
Mathematical anti-realism: the view that mathematical entities and truths do not exist independently of human minds, language, or cultural practices and are instead human constructions.
Mathematical realism: the philosophical view that mathematical entities and truths exist independently of human thought, language, or cultural practices.
Nativism: a theory in cognitive science and psychology which holds that certain

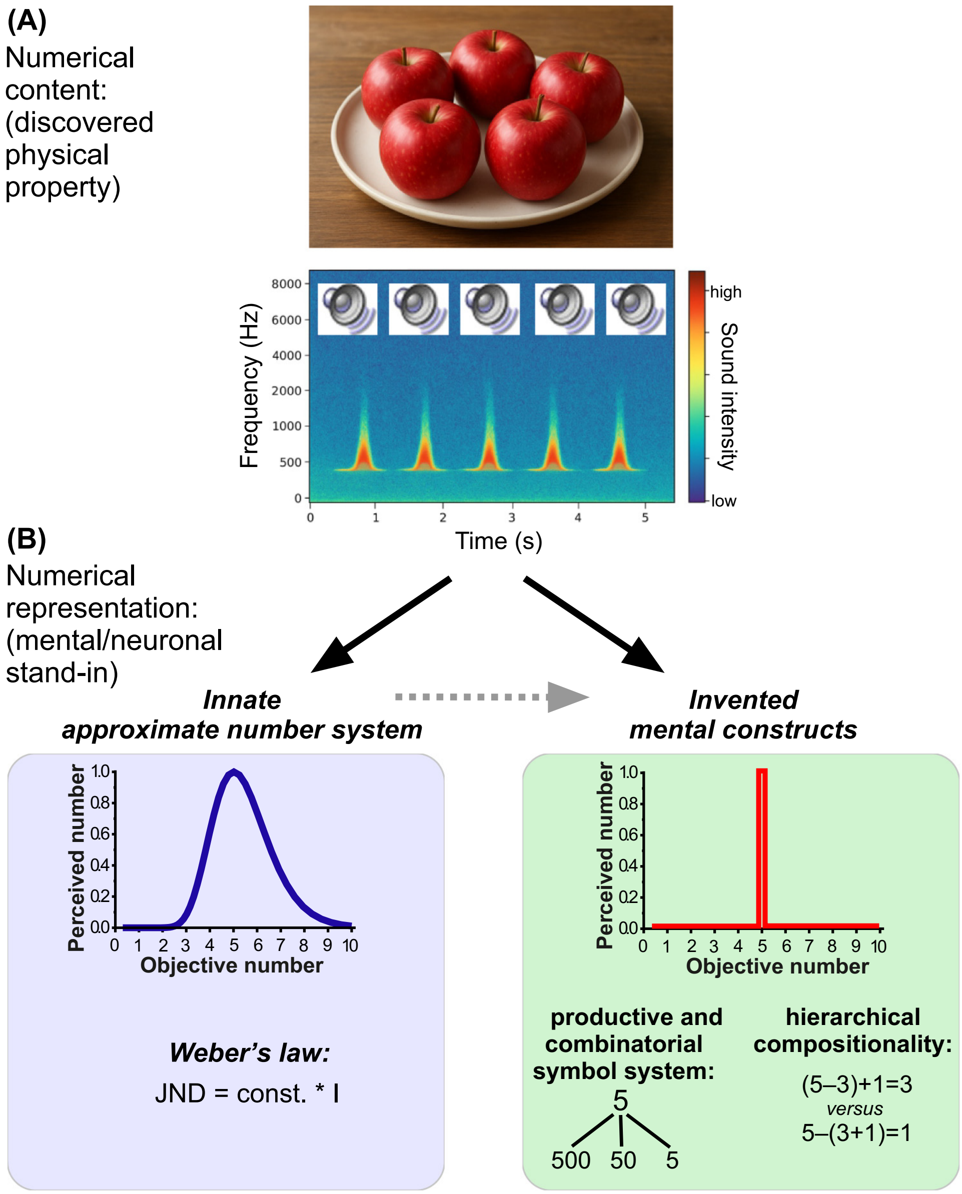

Figure 1. Distinction between the content of number and the representation of number. (A) 'The content of number (what?)' as a discovered physical property. Top: Five apples on a plate illustrating items distributed in space. Bottom: Sonogram of five sequential beeps illustrating items distributed in time. (B) 'The representation of number (how?)' as stand-ins. Left: Innate representations: Bell-shaped performance functions are the empirical (behavioral and neural) signature of an innate, nonsymbolic, analog (approximate) magnitude representation—the ANS—for numerical quantity. This representation is ratio dependent and follows Weber's law, which states that the JND between numbers increases (i.e., discriminability worsens) in proportion to numerical magnitude. The ANS is noncombinatorial and nonproductive. Right: Learned (invented) representations: Numerals and number words provide exact representations (e.g., for quantity 5) used for formal arithmetic. The place-value system constitutes a productive combinatorial symbol system: a finite set of digits combines with positional rules to generate an unbounded set of exact numerical expressions. The contrast between (5 – 3) + 1 = 3 and 5 – (3 + 1) = 1 illustrates that symbolic mathematics is a productive combinatorial system with hierarchical, structure-dependent interpretation: the meaning of an expression depends not only on its elements but also on their nested grouping. The dotted arrow reflects an integrated developmental trajectory in which symbolic number concepts are initially grounded in, and later partly differentiated from, the evolutionarily older ANS. ANS, approximate number system; JND, just-noticeable difference.

skills, abilities, or knowledge—such as language or number sense—are innate and biologically hardwired.
Number sense: an innate cognitive ability to intuitively perceive, represent, and estimate numerical quantities.
Ordinality: the position of items in a sequence (first, second, third, etc.).
Representational co-construction: the process by which biological predispositions and cultural learning interact to create progressively more powerful cognitive representations, shaping how objective content is encoded and used.
Sensorimotor or embodied numerical cognition: the proposition that numerical representations are grounded in the body and action systems (e.g., finger counting, grasping objects, eye movements during enumeration), such that perception, motor activity, and sensorimotor experience actively shape how quantities are perceived, processed, and manipulated.
Successor function: the principle that each natural number has a unique 'next' number—for example, the successor of 4 is 5—forming a basis of counting and the natural number sequence.
Symbol system: a structured network of symbols and combinatorial rules that enables the representation, manipulation, and communication of abstract concepts, allowing humans to encode complex ideas, reason systematically, and extend cognitive capacities; language and number theory are two prime examples of uniquely human symbol systems.
Weber's law: psychophysical law that states that the smallest detectable difference (just noticeable difference) between two stimuli is a constant proportion of their baseline intensity, or magnitude (*I*).

development and organization of numerical thought. This synthesis is especially timely, as advances in neuroimaging, cross-cultural studies, single-unit recordings, and **deep neural networks (DNNs)** are reshaping our understanding of how numerical abilities emerge and interact across biology, experience, and culture.

Nativism: discovered numerical content

Nativist theories propose that numerical competence is biologically endowed and evolutionarily conserved, with the ANS serving as an innate scaffold for representing numerosity by a **number sense** (Table 1) [8–10]. Behavioral evidence demonstrates that sensitivity to number is present within hours of birth: newborns, within their first 2 days of life, who heard sequences of a fixed numerosity (e.g., 12 sounds) looked longer at visual arrays with the same numerosity than at mismatched ones (e.g., 4) [11]. By 6 months, infants discriminate smaller 1:2 ratios across modalities and when continuous variables are controlled [12,13], reflecting an early-developing, biologically grounded system.

Phylogenetic evidence in animals supports deep evolutionary continuity. Diverse species, including bees, fish, birds, and primates, use numerical information spontaneously in the wild [14] and can be trained to discriminate numerosities [15]. Even sensorily naïve animals, such as newly hatched chicks, chicks incubated in darkness, and zebrafish larvae, exhibit spontaneous numerical discrimination, suggesting that number sense operates independently of prior sensory experience [16–20]. When animals discriminate numerosity, they do so approximately, producing a bell-shaped performance function that reflects their underlying nonsymbolic representational format, which follows **Weber's law** [21,22] (Figure 1B). The same signature appears in innumerate Indigenous groups when judging set size [23,24] and in numerate Westerners when symbolic counting is prevented [21]. This pattern reflects the primordial representational format of the innate ANS.

Neuroimaging studies in humans converge on a conserved cortical number network encompassing the intraparietal sulcus and prefrontal cortex (PFC) as core substrates for numerical processing [25–28], with functional continuity from early childhood into adulthood [29–32]. Infants as young as 3 months process numerosity via neural pathways distinct from those for object identity, with right parieto-prefrontal networks selectively responding to visual and auditory numbers [33,34]. Even fetuses in the final trimester exhibit mismatch responses to auditory numerical changes, indicating prenatal sensitivity to numerosity [35].

At the cellular level, neurons tuned to specific numerosities—responding selectively to particular number values regardless of perceptual features—have been identified in both human and

Table 1. Comparison of nativist, empiricist, and emergentist perspectives on numerical competence

Aspect	Nativism	Empiricism	Emergentism
Origin of numerical competence	Innate, biologically predetermined	Acquired through experience and culture	Arises from interaction between innate mechanisms and environmental input
Key mechanism	ANS	Language, education, and cultural practices	Neural plasticity, learning- and experience-driven refinement of initial capabilities
Evidence base	Infant studies, cross-species comparisons, and neuronal recordings	Cross-cultural research, linguistic analyses, and educational intervention studies	Developmental studies, neural network modeling, and neuroimaging evidence

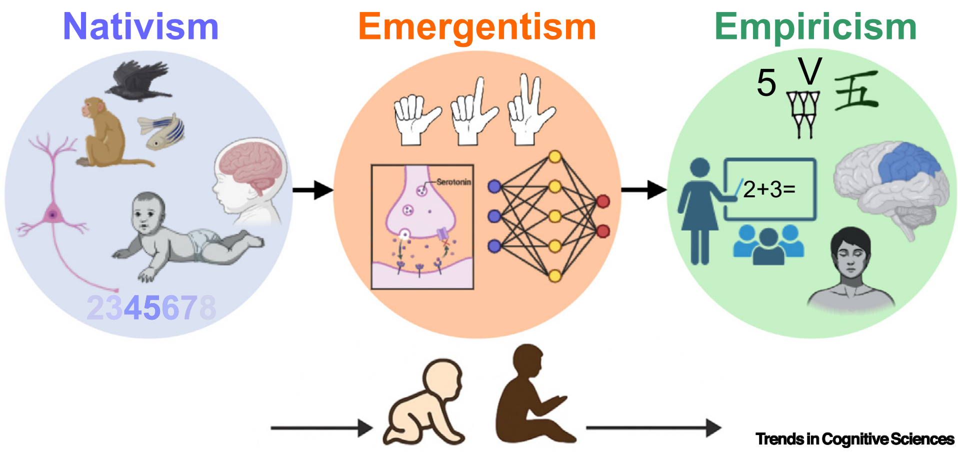

Figure 2. The coconstruction of number knowledge numerical cognition emerges through dynamic coconstruction. Left: Biologically grounded approximate number representations that can be found in newborns, infants, and across the animal kingdom provide the foundational content (blue). Middle: The central emergent layer (orange) illustrates how experience, learning, and neural plasticity integrate these components into mature numerical abilities. Right: Culturally invented symbolic formats—such as Hindu–Arabic numerals, Babylonian cuneiform, Latin notation, and Chinese numerals—support exact calculation, abstraction, and symbolic reasoning.

nonhuman primate brains [36–42]. Underscoring evolutionary continuity, such neurons have also been found in the independently evolved avian endbrain [43–47]. Critically, these neurons emerge without prior experience, appearing in numerically naïve monkeys [48], crows [49], chicks within a week of hatching [50], and zebrafish larvae a few days postfertilization [51,52]. Mirroring behavioral patterns, numerosity-selective neurons show bell-shaped tuning curves centered on their preferred value, indicating an innate neural code for numerosity (Figure 1B) [39,53].

Computational modeling further supports the nativist account. DNNs modeled on hierarchical visual systems [54] can spontaneously develop numerosity-selective units from varied visual input, even without any prior training [55], suggesting that architectural constraints alone can give rise to approximate number representations. However, it remains debated whether numerosity representations in untrained DNNs are truly abstract, supporting an innate number sense, or merely reflect sensitivity to correlated visual statistics [56].

In sum, converging evidence across behavioral, phylogenetic, neural, and computational domains supports the nativist claim that humans and other species possess an evolutionarily conserved, biologically instantiated number sense. The 'content' of set size, or numerical quantity, is thus discovered, emerging from intrinsic neural architectures independently of experience (Figure 2A).

Empiricism: invented numerical format

Empiricist accounts challenge nativist claims by emphasizing the roles of learning, experience, and culture in shaping numerical cognition (Table 1). Some empiricists deny that nonsymbolic representations are genuinely numerical [57–59], while others accept an innate sense of approximate numerosity but maintain that true number concepts only arise through cultural and experiential processes [60,61].

A first empiricist critique—the 'Not Number' argument—maintains that the number sense does not represent numerical representations at all. It is argued that nonsymbolic representations with their imprecision do not scale up to number and arithmetic, which require cultural mediation [57]. However, this objection rests on a mistaken assumption: it treats imprecision as evidence of a fundamentally different kind of representation. But the level of precision with which a property is encoded does not determine whether the representation is genuinely about that property. Just as height can be represented exactly (1.90 m) or approximately ('about 2 m') while still referring to the same property, approximate number representations are genuinely numerical; they simply encode quantity with lower precision [62].

Moreover, if number sense does not represent number, what does it represent? Empiricists suggest it may track continuous magnitudes—area, density, or duration—that covary with numerosity [58,59]. However, experimental evidence challenges this claim. Studies controlling continuous variables show that numerosity itself drives behavioral and neural responses [36,63–66]. Even the empty set, lacking items and, therefore, continuous magnitudes, produces standard numerical effects, such as the distance effect, and fits smoothly onto the mental number line across behavioral, neural, and computational studies [67–72]. Finally, when numerical and nonnumerical cues covary in stimuli, observers reliably prioritize numerosity [73–75]. Contrary to the 'Not Number' argument, these findings argue that numerical quantity is perceived directly, not inferred from other magnitudes.

A second objection holds that, although the ANS represents numerical quantity, it cannot encode exact numbers because it fails to discriminate small differences in large sets (e.g., eight vs. nine [61]). This seems to show that ANS representations lack the precision required for exact numerosity. But this criticism presupposes an all-or-nothing notion of discriminability—either a system can distinguish two numbers, or it cannot. However, because the ANS is ratio dependent rather than all-or-nothing, even very large numerosities (e.g., 999 vs. 1000) can still be discriminated above chance; it is only a question of enough exposure [76].

It is also argued that the ANS cannot represent natural numbers because it does not reflect the **successor function**; for example, it treats five as more similar to six than to four [61]. However, this assumes that representing number requires sensitivity to succession. Importantly, the relevance of the successor function differs for symbolic versus nonsymbolic representations. In exact, symbolic counting, **cardinality** and **ordinality** are intertwined: understanding '$n + 1$' requires grasping both sequence and set size, so the successor function effectively operationalizes ordinality [1]. By contrast, at the nonsymbolic level, approximate representations encode cardinality without requiring ordinality: infants and many animals can discriminate 'more versus less', and numerosity neurons reflect set size independently of order [39]. Thus, a system can represent numbers even if it does not encode their successor relations.

Compelling support for learned number representations comes from anthropology and developmental psychology, which indicate that exact number systems are learned rather than innate representations [77]. First, exact numerical systems are not universal: the indigenous Pirahã use only relative terms such as 'one', 'two', and 'many', while the Mundurukú employ approximate labels like 'threeish' or 'fourish' that give rise to approximate bell-shaped performance functions (Figure 1B) [23,24,78]. Second, exact number systems are culturally variable, using diverse notations ranging from direct body-based systems to derived place-value systems with different bases [79]. Third, numerical concepts historically emerged to solve practical problems, from counting tokens to abstract place-value systems and eventually to full number theory (Figure 1B) [80,81]. Fourth, exact systems relied on physical counting aids, such as fingers or knotted ropes, reflecting cultural scaffolding rather than innate abstraction [24,82]. Fifth, children likewise acquire exact symbolic number concepts gradually and on culturally variable timelines [61,83,84]. Finally, cross-cultural variability in the timing and pace of symbolic number acquisition further underscores the role of learning and enculturation [85]. These findings support the view that symbolic number is a cultural construction [77].

Some empiricists go further, proposing that symbolic numbers are constructed by combining nonnumerical representations, akin to building complex programs from basic components [61,77,84]. However, this strategy risks circularity: to combine nonnumerical primitives into a representation of exact number, the system must already know which combinations count as numerical and why. In other words, the constructive process seems to require a prior grasp of numerical structure, i.e. criteria for exactness, ordering, or cardinal identity, thereby presupposing precisely the number concept it is meant to generate.

Neuroimaging evidence indicates that the connection between symbolic and nonsymbolic numbers may be more limited than nativist accounts assume, emphasizing learning [86–88]. While early studies suggested shared cortical substrates for symbolic and nonsymbolic numbers [89], later multivariate analyses reveal distinct activation patterns [90–92]. Cross-format neural similarity predicts arithmetic ability in children aged 7–10 but declines in adolescents and adults, suggesting developmental constraints [93]. Short-term training produces neural changes paralleling long-term developmental reorganization [94]. Finally, single-neuron recordings in humans show separate neurons for nonsymbolic numerosity and symbolic numbers, with no overlap, suggesting that the brain represents these two types of numbers differently [41].

Computational models mirror these findings. DNNs trained on varied input can learn to map non-symbolic to symbolic quantities, reorganizing internal tuning functions to yield precise numerosity representations [95]. Even when spontaneous number-selective units are removed, such networks still learn symbolic mappings, implying that numerical abstraction arises primarily from experience-dependent optimization rather than innate architecture.

Together, empiricist evidence converges on a clear conclusion: while approximate numerical sensitivities may be biologically grounded, exact symbolic systems arise through learning, cultural practice, and neural plasticity (Figure 2). The 'format' of numerical representation is culturally invented, giving rise to precision, combinatorial capacity, and symbolic depth of numbers.

Emergentism: interactive numerical development

Emergentist perspectives propose that numerical cognition arises from continuous interactions between biologically prepared perceptual systems and experience-dependent learning (Table 1). Emergentist accounts emphasize that numerical abilities are jointly shaped by neural architecture, environmental statistics, and symbolic acquisition (Figure 2).

In support of this view, newborns and infants initially display coarse sensitivity to numerosity, which sharpens with age and exposure to structured numerical environments [11,12]. Improvements in ratio discrimination—from coarse 1:3 distinctions in infancy to near-adult 9:10 precision—track both neural maturation and cumulative interaction with number-rich contexts. Early ANS acuity predicts later symbolic math performance [96–98], indicating that approximate and exact number systems develop interactively rather than independently. Cross-cultural findings reinforce this view: formal education enhances ANS precision, as observed among the Mundurukú, and transforms mental number-line scaling from logarithmic to linear [99,100]. Experience thus amplifies and refines early perceptual sensitivities, yielding increasingly precise numerical representations. Within the emergentist framework, formal mathematical training selectively improves ANS acuity because experience primarily fine-tunes neural systems already predisposed to represent numerosity, leaving unrelated perceptual systems (e.g., size perception) largely unaffected [100]. This illustrates domain-specific, content-sensitive plasticity in numerical cognition.

Comparative and computational studies converge on a shared principle: innate representations provide an initial scaffold that is continuously updated through experience. For example, humans, monkeys, and crows share biased numerosity judgments, which are well captured by **Bayesian models** in which noisy sensory evidence is integrated with learned regularities [101]. In this view, the brain's number system operates as a dynamic estimator, combining evolved predispositions with adaptive learning to support number decisions. Similarly, numbers are organized along a 'mental number line', whose orientation and scaling emerge from the interaction of biologically grounded spatial biases with culturally learned ordering conventions [102].

Developmental neuroimaging reveals progressive reorganization of numerical networks across childhood. Young children recruit prefrontal regions for effortful number judgments, whereas adults increasingly rely on the intraparietal cortex for automatic processing [103,104]. This frontal-to-parietal shift reflects increasing efficiency and specialization in typically developing children and is delayed in **developmental dyscalculia** [105]. Arithmetic follows a similar trajectory: early reliance on prefrontal and hippocampal systems gives way to left posterior parietal engagement as computation becomes automatized [106]. Paralleling early human stages, numerosity–sign associations emerge first in the PFC in monkeys [107]. Numerical training in monkeys increases neuronal selectivity and precision [108], illustrating how experience fine-tunes biologically prepared circuits.

According to the emergentist framework, neurons encoding symbolic numbers are predicted to partially diverge from numerosity neurons over development. Early in life, numerosity neurons provide a broad, approximate scaffold that is mapped onto symbolic numbers, consistent with the **mapping hypothesis** [96,109], resulting in partial overlap between the two populations. With experience and formal education, symbolic-number neurons become increasingly specialized and distinct, encoding exact values and supporting combinatorial arithmetic, in line with the **estrangement hypothesis** [92,93], while numerosity neurons remain approximate and ratio dependent. Residual interactions persist, allowing symbolic processing to draw on approximate magnitude representations when necessary. This developmental trajectory is supported by single-neuron recordings in humans showing distinct neuronal populations selective for either symbolic or nonsymbolic numbers [41], and by developmental neuroimaging demonstrating that cross-format neural similarity is strong in children but decreases with age, reflecting increasing specialization [93].

The emergentist account additionally predicts systematic cultural variation in how symbolic-number neurons specialize: differences in numerical notation, reading direction, and educational intensity should influence how quickly symbolic codes differentiate from approximate ones and how strongly symbolic–nonsymbolic coupling persists. Cultures with reduced exposure to exact number words or limited formal schooling are expected to exhibit greater neural overlap between symbolic and approximate representations, whereas cultures with explicit, intensive numerical instruction should show stronger estrangement and more specialized symbolic-number coding.

Computational modeling corroborates emergentist principles. DNNs can spontaneously develop number-selective units from variable visual input [110], with tuning strength predicting enumeration accuracy, thus mirroring behavioral and neural data [71,111]. Numerosity sensitivity often appears before explicit training and refines through exposure, consistent with domain-general learning mechanisms [112]. Moreover, dual-stream architectures exhibit 'zero-shot' counting, generalizing to novel numerosities without supervision [113]. Yet even advanced multimodal AI systems struggle with larger numbers, underscoring that architecture alone is insufficient and experience is essential for precise numerical competence [114].

In sum, emergentist accounts hold that numerical cognition arises from the interaction of innate predispositions with experience, such that numerical representations are progressively constructed—and reorganized—through development, learning, and neural plasticity. Within the emergentist framework, the link between the ANS and symbolic numbers is understood as a coordinated neural, experiential, conceptual, and instructional process (Figure 1; dotted arrow). At the neural level, early numerosity-tuned neurons provide an approximate scaffold onto which symbolic numbers are initially mapped, yielding partial cross-format overlap in childhood. Experientially, children observe that number words and digits reliably track quantities, enabling stable associations between symbolic tokens and approximate magnitudes. Conceptually, these experiences support the construction of exact numerical meanings that progressively exceed the representational limits of the ANS. Instruction serves as a catalyst: structured counting, mastery of exact number words, and formal arithmetic promote increasing specialization—and eventual partial estrangement—of symbolic-number representations from the underlying approximate code (Figure 1; straight arrow between content and symbols). Thus, the link between the ANS and symbolic numbers reflects an integrated developmental process through which symbolic number concepts are initially grounded in, and subsequently differentiated from, the evolutionarily older ANS.

The emergentist framework is fully compatible with **sensorimotor or embodied perspectives on numerical cognition** [115,116]. It proposes that numerical representations are grounded in bodily actions and sensorimotor experience, which shape how quantities are perceived and processed. Sensorimotor mechanisms provide structured, action-based input—such as finger counting, eye movements, or vocalizations during enumeration—that scaffolds both ANS and symbolic-number development [45,117]. Within the emergentist account, these action-based mechanisms constitute additional nonsymbolic numerical representations that interact with the ANS, supporting the formation of stable mappings between quantities and symbols and explaining how cultural practices (e.g., reading direction) shape number–space associations and symbolic-number processing.

Co-constructed minds: integrating innate predispositions and cultural formats

The origins of numerical cognition cannot be captured by a single explanatory framework. Humans are born with a biologically grounded sensitivity to numerosity, a discovered content reflecting deep evolutionary continuity. Through language, education, and cultural invention, this foundation is transformed into precise, symbolic systems which is built on invented formats that enable arithmetic, abstraction, and mathematics. By distinguishing content from format, nativist and empiricist insights can be reconciled within a unified framework of representational co-construction. Numerical cognition, in this view, is not a fixed capacity but a dynamic synthesis of evolution, experience, and culture. Understanding this synthesis provides a model for how the human mind converts perceptual intuitions into symbolic thought, how the world, in being represented, is both discovered and invented.

The proposal that innate content and learned formats work together to build complex cognition provides a useful framework for rethinking the traditional nativist–empiricist debate. Rather than asking whether abilities are innate or learned, this framework asks which components reflect objective features of the world and how these features are represented. This perspective yields concrete, testable predictions across other human cognitive domains such as geometry and language.

Humans and many animals exhibit an innate perceptual scaffold for spatial and metric content, elaborated through culturally invented geometric formats such as maps, measurement systems, and Euclidean proofs [118]. Infants and nonhuman species show modality-independent sensitivity to distance, angle, and layout, consistent with a biologically prepared 'core geometry' system [119–123]. Formal geometric reasoning—axioms, coordinate systems, and symbolic notation—emerges only through education and tool-mediated practice that transforms intuitive spatial representations into precise, combinatorial structures [61]. This framework predicts that early parietal networks support coarse metric representations shared across species, whereas frontoparietal circuits are progressively recruited and reorganized through schooling and cultural experience to support abstract geometric inference.

Language provides a clear parallel. Humans possess innate constraints for linguistic content—universal sensitivities to phonology, hierarchical syntax, and compositional structure—while the formats of grammar, lexicon, and symbolic convention are culturally invented and transmitted. Nativist theories posit an evolved 'Universal Grammar' that enables rapid acquisition and constrains linguistic variation [124,125]. Usage-based and constructivist accounts, by contrast, emphasize the roles of joint attention, communicative intent, and statistical learning in shaping linguistic structure [126,127]. Within a content–format framework, early linguistic predispositions reflect discovered biological content, while linguistic diversity, vocabulary, and pragmatic norms reflect invented cultural formats. Neural and developmental evidence supports this synthesis: early perceptual and syntactic sensitivities are biologically prepared but become progressively tuned through exposure, producing both cross-linguistic universals and culturally specific forms.

Concluding remarks

Numerical cognition shows how biological predispositions and cultural inventions jointly shape the mind. Innate sensitivities to approximate quantity provide an initial scaffold, but symbolic systems, such asnumber words, notation, and arithmetic, transform these early capacities into the rich numerical abilities seen in humans. Distinguishing numerical content from representational format highlights this interaction and positions numerical knowledge as a product of coconstruction rather than solely nature or nurture.

Looking forward, the content–format framework encourages tracing how perceptual foundations are progressively reorganized through cultural tools and formal instruction (see Outstanding questions). This approach points to new developmental predictions, suggests targeted avenues for supporting learners—including those with dyscalculia—and offers design principles for AI systems that acquire number in a more human-like manner. More broadly, representational co-construction may illuminate how abstract concepts emerge across domains such as geometry, language, and logic, offering a general template for understanding the origins of human symbolic thought.

Outstanding questions

How do approximate and symbolic number representations interact across development, and which neural mechanisms support this mapping?

Which brain circuits integrate nonsymbolic and symbolic numbers, and how can this knowledge inform interventions for dyscalculia?

How does representational coconstruction vary across cultures, and how do these differences shape numerical reasoning and mental number scaling?

Can computational models replicate human developmental trajectories and cultural variability in number learning, and what constraints are essential?

How does formal education refine approximate number representations and reorganize neural networks, and are there sensitive periods for these effects that could be used for interventions in mathematical learning disabilities?

Do principles of representational co-construction extend to other domains, such as geometry, spatial reasoning, and language, and what mechanisms are shared?

How can understanding human numerical cognition guide artificial intelligence systems capable of flexible symbolic and approximate reasoning?

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Declaration of interests

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