Iconic and non-iconic stages in number development: The role of language

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Is language the key to number? This article argues that the human language faculty provides the cognitive equipment that enables humans to develop a systematic number concept. Crucially, this concept is based on non-iconic representations that involve relations between relations: relations between numbers are linked with relations between objects. In contrast to this, language-independent numerosity concepts provide only iconic representations. The pattern of forming relations between relations lies at the heart of our language faculty, suggesting that it is language that enables humans to make the step from these iconic representations, which we share with other species, to a generalised concept of number.

Over the last two decades, evidence coming from developmental psychology, comparative psychology and cognitive ethology has revealed a grasp of quantitative concepts in preverbal infants and higher animals that presumably has developed independently of and prior to language [1-5]. Does this mean that our concept of *number* is independent of language? The answer I will give is 'no': integrating these early numerosity representations into a broader account of numerical thinking, I will argue that language plays a crucial role in the emergence of a systematic number concept in humans.

As a basis for our discussion, I first make clear what this number concept involves, focussing on the non-iconic character of number assignments. Against this background I characterise pre-linguistic numerosity concepts as iconic precursors of numerical thinking. I review the evidence for early iconic stages in number development, and will then discuss the role of the human language faculty in transcending these iconic stages on the route to number. In particular, I show that language provides a cognitive pattern of 'dependent linking' that is crucial for the development of number assignments, suggesting that the emergence of language as a mental faculty laid the ground for our concept of number.

The non-iconic nature of number assignments

A striking feature of numerical thinking in humans is its flexibility. Numbers can be used in a wide variety of contexts, where they assess different properties of empirical objects (individual objects as well as sets), in cardinal number assignments (e.g. 'nine cats') as well as in ordinal ('the ninth runner') and even nominal number assignments ('the #9 bus').

The features that make these different kinds of number assignments meaningful have been analysed within the Representational Theory of Measurement [6,7], a theory that has been developed within the fields of philosophy and psychology and provides the criteria ensuring that the number we assign to an object does in fact tell us something about the empirical property we want to assess.

For our discussion, a crucial result from this analysis is that number assignments are primarily about relations: in number assignments, we associate relations between numbers with relations between empirical objects. In the simplest case, that of nominal number assignments, the numerical relation '=' (or '≠') is associated with the empirical relation 'is (non-)identical with', e.g. when we distinguish different bus lines by different numbers.

In ordinal number assignments we associate the ordering relation in our number sequence, '<' or '>', with the relative ranks of objects within an empirical sequence, for instance with the ranks of runners in a race where '<' is associated with 'finished faster than' (hence if one person, A, ends up as the seventh runner, and another one, B, finishes as the ninth runner, then this means that A was faster than B, because 7 < 9).

In cardinal number assignments the empirical objects are sets, and we associate the numerical relation '>' with the empirical relation 'has more elements than': the more elements a set has, the higher the number it receives, hence positions in the number sequence serve to identify the cardinality of empirical sets. A common verification procedure for this kind of number assignment is counting. When counting objects, we establish a one-to-one mapping between the elements of a set and an initial sequence of natural numbers. This one-to-one mapping ensures that we employ exactly as many numbers as there are objects, that is, it makes sure that the counted set and the set of numbers we use in the count have the same cardinality. Since the numbers form a fixed sequence, we always end up with the same number for sets of the same cardinality. Hence, this number can be used to identify the cardinality of a set, and it can do so due to its position in the number sequence.

It is this association of relations that constitutes number assignments: a correlation between numbers and objects that depends on the relationships in which these numbers and objects stand in their respective systems. Let us call this kind of linking '(system-)dependent linking' [8:Ch.1]. Figure 1 gives an illustration.

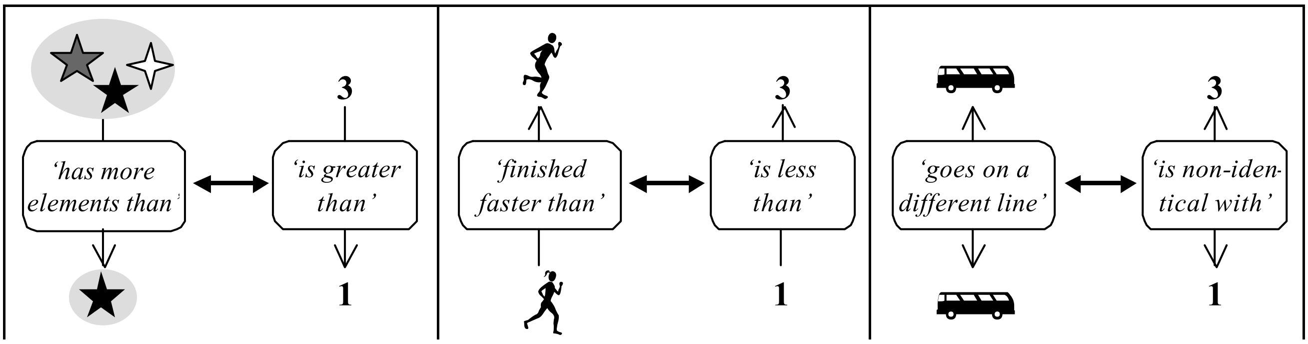

Figure 1: 'Dependent linking': Number assignments are based on associations of relations

Crucially, this kind of linking does not access numbers and objects as individuals, but as elements of two systems. It is for this reason that numbers are not confined to cardinality, but can be employed to identify cardinal, ordinal, and nominal relations alike: the linking is *non-iconic*, it is not based on similarities between individual numbers and empirical objects, but on numerical and empirical relations.

In contrast to this, icons share some features with their referents, they are similar to the objects they refer to (Box 1 below will give the semiotic background for icons). These features can be visual ones like shape as in the case of the icon ♿ that resembles the silhouette of a wheel-chair user, but they can also be properties of sets, like cardinality. An example for a cardinal icon is that of tallies, for instance those used by waiters to keep record of the drinks a customer has to pay. In this case, there are as many tallies as served drinks: one represents elements of one set (a set of drinks) by elements of another set (the set of tallies).

Hence unlike number assignments, iconic representations are not based on dependent linking. The set of tallies is associated with the set of objects it represents via similarity, it has the relevant feature – namely a certain cardinality – itself and does not relate to a system.

As a result, icons do not provide the kind of flexibility that numbers give us. They are specialised for a particular property (e.g. cardinality), since the representation draws on individual similarity, whereas numbers, which draw on relations within a system, are flexible tools that we can use to assess cardinal, ordinal, and nominal relations alike.

And unlike that of numerical representations, the grasp of icons is limited to a small perceptual range: iconic representations of cardinality work well for sets of one to three elements, but become fuzzy for bigger sets (imagine representations consisting of, say, 102 versus 103 tallies).

With this distinction in mind, let us have a look at the status of the early, language-independent numerosity representations.

Before language: numerosity representations in animals and human infants

Evidence from animal studies suggests that our concept of cardinality can build on an evolutionarily old capacity that we share with other vertebrates: mammals and birds have been shown to discriminate between sets of one, two, and three elements and to perform simple arithmetic transformations on them, and to distinguish sizes of larger sets if the difference is big enough [cf. 9-14 and overviews in 2,4], and recent evidence suggests that a rudimentary capacity to distinguish small numerosities might even be present in amphibians [15]. This indicates that cardinality can be grasped by nonhuman animals – that is, species that do not possess the human language faculty as part of their biological heritage [16] – and should hence be independent of language.

What is more, this early capacity seems also to exist in preverbal infants: a large body of literature suggests that infants can discriminate sets of different sizes and react to transformations on them [3; 17-22] (although clues like surface area [24] or the familiarity of set sizes [25], might also play a role in these tasks). While it is controversial whether our grasp of cardinality is inborn or whether infants rely initially on continuous quantitative clues and only later develop discrete representations [26], the important point for our discussion is that these findings indicate that cardinality representations are available at some point prior to language development.

Taken together, this evidence, then, suggests a biologically determined, evolutionarily old and language-independent concept of cardinality. How does this relate to our claim that language holds the key to number? Let us have a look at the nature of this early concept. Two main sources have been proposed for it: object files and analog magnitudes. Most accounts agree that both kinds of representations are employed in early numerical reasoning, although it is controversial to what extent [27,28].

Object files are mental tokens that represent the elements of a quantified set and are filed in short-term memory [2,28-30]. This filing activity can hence be seen as a mental equivalent to the kind of tallying we discussed above: a distinct representation (an object token) is produced for each object in the quantified set, yielding exactly as many tokens as objects. The mechanism generating analog magnitudes, on the other hand, has been described as an accumulation of continuous quantities in proportion to the number of quantified elements [31]. While object files provide precise representations of cardinality, but are limited to small sets (supporting tasks like '1+1' or '2 versus 3'), analog magnitudes yield fuzzy representations, but can also support the grasp of larger set sizes (as in tasks like '8 versus 16') [5,32,33].

Crucially, object files as well as analog magnitudes represent the size of a set via representations of its elements: each element corresponds to a distinct object token or to an increment of the analog magnitude, respectively. This yields *iconic* representations of set sizes; representations that do not rely on dependent linking, but are associated by individual similarity with the objects they represent: the size of an empirical set is represented by the cardinality of another set (a set of object tokens) or the size of an analog magnitude (in this latter case the representation is not one of discrete cardinality, but of accumulated quantity, suggesting that cardinal concepts based on object tokens play a more central role for the development of discrete numerical representations [8,28,34]).

Early numerosity representations hence suggest an iconic basis of number development; they support iconic stages before the emergence of dependent linking in the numerical domain. Evidence for such iconic stages can be found both in human history and in the individual acquisition of numbers.

Evidence for early iconic stages in number development

Excavations of carved bones from approximately 30,000 years ago suggest that the use of notches goes back at least as far as Stone Age [35], and the same is probably true of finger counting, another way to represent the cardinality of sets iconically. Traces of these icons can still be found in non-verbal numerals like Roman I, II and III or Chinese , and (which are reminiscent of sets of notches), and in number words like <u>five</u> (which relates to a Proto-Indoeuropean word for 'fist', as an indication of five fingers [36]).

Studies on the acquisition of counting words and numerals provide evidence for such iconic stages in *individual development*. Before about 3½ years of age, children often give a sequence of counting words when asked 'How many', for instance they might go 'one-two-three-four-five', but without answering 'five' in the end [37]. Note that this qualifies as an iconic representation of cardinality. What children at this stage do is produce one counting word for each object, but they do not use a single element (i.e., the last word in the count) to represent the cardinality of the whole set, based on the relations that hold within the counting sequence.

This means that the counting words work like verbal tallies at this stage: since the children produce exactly as many counting words as there are objects, the set of these counting words can serve as a verbal icon for the objects' cardinality, just like fingers and notches serve as visual icons and mental tokens as mental icons (see Box 1).

Evidence from studies on the acquisition of Arabic numerals indicates that children initially tend to employ them, too, as icons: in order to indicate a cardinality they often write down a sequence of numerals instead of a single numeral, e.g. '123' instead of '3'; or they use sets of repeated digits, for instance '333' instead of '3' [38,39]. In both cases, we observe an *iconic* representation of cardinality: the cardinality of one set, the objects, is represented by that of another set, the numerals.

Box 1: Iconic representations of cardinality

Following a semiotic taxonomy as introduced by Charles Sanders Peirce [48] we can distinguish three kinds of signs: symbols, indices, and icons. In symbolic reference, the link between sign and object is established by convention, as in the case of human languages. In indexical reference the sign is related to the object by a physical or temporal relation. In *iconic* reference the sign shares some features with its referent. An instance of such signs are cardinal icons; in this case the shared feature is cardinality.

Cardinal icons yield representations that are based on an enumeration of elements ('an object, and another object, and another object') rather than on an assignment of a number to the whole set ('3 objects'). These representations can be captured formally with the help of numerically definite quantifiers [49,50] of the form $\exists_{nx}$, where n is a natural number and $\exists_x$ is an existential quantifier binding x (F is a predicate identifying the objects):

$\exists_{0x}$ (Fx) $\Leftrightarrow$ $\neg\exists_x$ (Fx) ['There are 0 Fs.']

$\exists_{(n+1)x}$ (Fx) $\Leftrightarrow$ $\exists_x$ (Fx $\wedge$ $\exists_{ny}$ (Fy $\wedge$ $\neg$ (y = x))) ['There are n+1 Fs.']

There are two requirements for tokens to work as an iconic cardinality representation: (1) the tokens must be distinct (so that the set of tokens *has* the property of cardinality) and (2) there must be exactly one token for each element of the represented set (so that the set of tokens has *the same cardinality* as the set it represents). These requirements are met not only by tallies like notches and fingers, but also by the mental object tokens proposed for the representation of small sets, and by elements of verbal or visual number sequences in their usage at early acquisition stages, when sets of spoken number words or written numerals are used to represent sets of objects.

Figure 2 illustrates the status of object tokens (depictured as dots in the graphic), fingers, counting words, and numerals as iconic cardinality representations at early developmental stages.

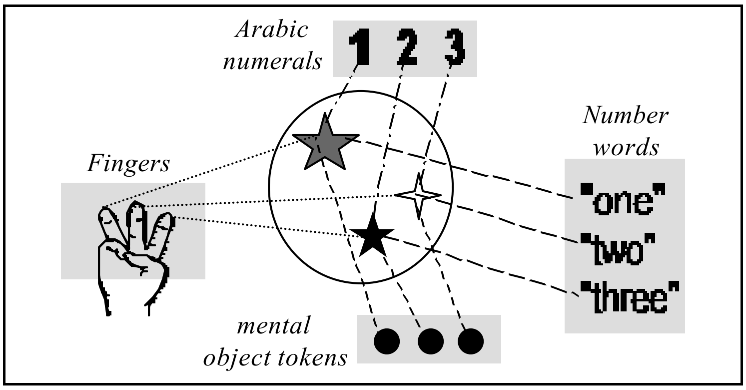

Figure 2: Mental, visual, and verbal tallies can serve as cardinal icons for a set of stars

In view of our analysis of number assignments we can hence characterise these representations as *pre-numerical*. They are on a par with other pre-numerical concepts that we also share with other species, namely early concepts of serial order and sequential ranks [40-42] and of individuation and (non-)identity [43], which allow us to grasp the relevant empirical property in ordinal and nominal number assignments, respectively. Similarly, numerosity representations support our grasp of cardinality, hence one of the properties we assess with numbers – as opposed to numbers themselves, our tools in assignments that are based on dependent linking.

What made it possible for humans to make the step from these early, pre-numerical concepts to systematic numerical cognition? It is at this point that language comes into the picture: in the following section I show that dependent linking is made available as a cognitive pattern by our language faculty.

Language provides a cognitive pattern of dependent linking

From a semiotic perspective, there are two central characteristics of human language as a symbolic system: (1) the arbitrary, conventional basis for the association of signs and their referents ([44]; cf. also Box 1 above), and (2) the option to generate an unlimited number of complex signs [16]. These two features can co-exist because linguistic symbols are always part of a system, and they refer to objects with respect to their position in that system: linguistic symbols – unlike icons – are not associated with their referents by individual similarity, but draw on systematic sign-sign relationships, and it is this feature of language that makes it possible to derive an interpretation for any well-formed complex sign.

For instance in the English sentence "The dog bites the rat." one can identify the dog as the attacker and the rat as the victim, because the noun phrase 'the dog' comes before the verb, which is the position for the subject in English, and 'the rat' comes after the verb, in object position, and the noun phrases in these positions denote the Agent (attacker) and the Patient (victim) of the 'biting'-action, respectively. So the connection one makes is between (a) symbolic relations like 'The words *the dog* come before the word *bites*' or 'The noun phrase *the dog* is subject of the verb *bite*' and (b) relations between referents (more accurately, conceptual relations: relations between objects represented by our conceptual system), namely ‘The dog is the Agent in the biting-event’; and similarly for the rat:

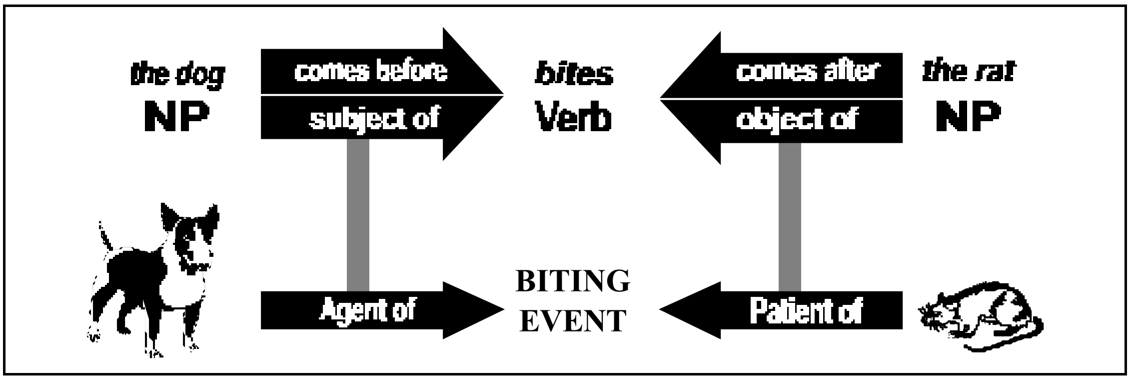

Figure 3: An example for the association of symbolic and conceptual relations: ‘The dog bites the rat’

Whereas at early stages of language evolution the relevant symbolic relations were presumably just linear ones (‘comes before/after’), later stages involve hierarchical relations (‘subject of’/‘object of’) [45,46]. In either case, the association between symbols and their referents is determined by the respective relations that hold between them, and this pattern can been regarded as the main step in the emergence of human language [47]: it is the crucial feature that distinguishes human languages from animal communication systems and is responsible for the success of language as a mental faculty in our species.

Ultimately, this means that our language faculty provides a cognitive pattern of *dependent linking*: in linguistic reference we associate symbolic relations with relations between objects – just as in number assignments, we associate relations between numbers (for instance ‘>’) with relations between empirical objects (for instance ‘has more elements than’). This, then, shows us a way how systematic numerical cognition could have evolved in the development of our species (cf. also [8:Ch.4]). Once language was in place, our species had the mental equipment to make the crucial step from early iconic representations to a generalised concept of number: our language faculty enables us to associate relations by way of dependent links, and by doing so, allows us to grasp the logic of non-iconic number assignments.

Conclusion: Language as a key to non-iconic numerical cognition

In this article I discussed the distinctive way in which numerical cognition is intertwined with the human language faculty. I characterised the human number concept as a unified concept that encompasses cardinal, ordinal, and nominal aspects alike, and is based on a pattern of linking up relations between numbers with relations between objects. This pattern, which I called '(system-)dependent linking', allows us to make the step from pre-numerical (and pre-linguistic) iconic representations to systematic numerical thinking. I argued that the key to this development, the cognitive capacity that provides this pattern of dependent linking, is the human language faculty: dependent linking is the core feature that defines language as a species-specific trait, suggesting that it is no accident that the same species that possesses language as a mental faculty should also be the one that developed a systematic concept of number.

Box 2: Questions for future research

Laboratory studies with non-human primates and parrots suggest that some animals might be able to learn to use combinatorial signs [51,52]. Does this indicate an ability for the association of relations, that is, for dependent linking, at least in a way that is based on linear (if not hierarchical) sign-sign relations?

Does such an ability provide a basis for the association of relations in the numerical domain? The evidence available so far suggests that apes, dolphins, and birds can learn to use arbitrary signs for cardinalities [52-55], and apes have also been taught to arrange such symbols sequentially [55-58]. Can these animals also learn to systematically draw on relations within the number sequence, that is, to use the sequence as a tool that can be employed to indicate different kinds of empirical relations (cardinal, ordinal, and even nominal)?

Can animals be taught a number sequence as an ordered list of non-referential, arbitrary items, similar to the way children initially acquire number words (namely "as a rote list of meaningless words" [37:132])? And if so, does that eventually enable them to grasp the relations in this sequence (hence, among others, to comprehend that each number has a unique successor) and to learn to use these numerical relations in systematic number assignments?

Ritualised routines have been suggested as a crucial factor both in the origin of counting [59,60] and in the emergence of symbolic thinking [47:Ch.12], and in particular for the pattern characterised above as 'dependent linking'. What is the developmental status of these routines? Do rituals provide a cognitive basis for the emergence of dependent linking?

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