

Quantities, amounts, and the numerical core system

Avishai Henik^{1*}, Tali Leibovich², Sharon Naparstek¹, Liana Diesendruck³ and Orly Rubinsten⁴

¹Department of Psychology, Zlotowski Center for Neuroscience, Ben-Gurion University of the Negev, Beer-Sheva, Israel

²Department of Cognitive Sciences, Ben-Gurion University of the Negev, Beer-Sheva, Israel

³Department of Computer Sciences, Ben-Gurion University of the Negev, Beer-Sheva, Israel

⁴Department of Learning Disabilities and Edmond J. Safra Brain Research Center for the Study of Learning Disabilities, University of Haifa, Haifa, Israel

*Correspondence: henik@bgu.ac.il

Numerical cognition is essential to many aspects of life and arithmetic abilities predict academic achievements better than reading (Estrada et al., 2004). Accordingly, it is important to understand the building blocks of numerical cognition, the neural tissue involved, and the developmental trajectories. In the last two decades research has made impressive strides forward in studying numerical cognition and brain mechanisms involved in arithmetic. This advance was marked by suggestions of a numerical core system that can be characterized as a set of intuitions for quantities innately available to humans (Brannon et al., 2006) and animals (Cantlon and Brannon, 2007). We suggest that another system, evolved to perceive and evaluate non-countable dimensions like size or amount of substance may be important for the evolution of the numerical system and numerical abilities. The current opinion article examines this idea and the possible interplay between, on the one hand perception and evaluation of continuous dimensions and, on the other, the numerical system.

NEUROCOGNITIVE BASIS FOR QUANTIFICATION

Several behavioral effects have been well documented in the field of numerical cognition. Amongst them are: subitizing, counting, and the distance effect. The first and second refer to the processes involved when participants are asked to enumerate – report the number of items in an array. Here, performance is best described as a biphasic graph: their reaction time (RT) rises slowly, between 40 and 100 ms per item, up to four items, and then rises steeply at a rate of 250–350 ms per item (Jevons, 1871; Trick and Pylyshyn, 1994). It seems that four items (or less) can be grasped almost simultaneously with no effort; this is termed subitizing (Kaufman et al., 1949). In contrast, for five to nine items, participants are engaged in an effortful counting

process. The third behavioral effect, the distance effect, arises when participants are asked to compare two arrays of dots, or two numerals. RT decreases with increase in the distance between the to-be-compared stimuli. This numerical distance effect was first reported by Moyer and Landauer (1967) who suggested that people convert written or auditory numbers into analog magnitudes. The effect has been reported by many other researchers under various conditions (Banks et al., 1982; Dehaene, 1989; Link, 1990; Tzelgov et al., 1992; Schwarz and Heinze, 1998). Further research showed these effects (e.g., subitizing, counting, and distance) can be found in infants and animals. For example, the numerical distance effect has been found in children (Sekuler and Mierkiewicz, 1977; Mussolin and Noël, 2007; Holloway and Ansari, 2008; Landerl and Kölle, 2009), and in primates (Brannon, 2003; Cantlon and Brannon, 2006). In addition, the various effects are compromised in developmental dyscalculia (DD) or mathematical learning disability (MLD) (for subitizing and counting: Koontz and Berch, 1996; Geary et al., 1999; Landerl et al., 2004; Moeller et al., 2009, for the distance effect: Price et al., 2007; Rousselle and Noël, 2007; Mussolin et al., 2010). Finally, many reports have suggested involvement of the parietal lobes and in particular the intraparietal sulcus (IPS) in numerical cognition (Dehaene et al., 2003; Fias et al., 2003; Ansari et al., 2006; Cohen Kadosh et al., 2007a).

This accumulated body of results led to a widely accepted view of an innate domain-specific foundation for arithmetic. In particular, it has been claimed that there is a core numerical system, the basis of which is the ability to perceive and manipulate discrete quantities (e.g., enumeration of dots) (Ansari, 2008; Dehaene, 2009; Butterworth, 2010; Piazza, 2010). In addition, it has been conjectured that arithmetic disability involves a domain-specific deficit in the capacity to enumerate (Butterworth, 2010;

Piazza, 2010). However, careful scrutiny of the literature suggests that to achieve a comprehensive picture of numerical cognition other factors need to be examined.

CAREFUL EXAMINATION OF CORE QUANTIFICATION

A survey of the literature raises several interesting observations; (1) similar to their sensitivity to discrete quantities (e.g., enumeration of dots), infants show sensitivity to non-countable continuous dimensions like area (Brannon et al., 2006), line length (de Hevia and Spelke, 2010), and size (Lourenco and Longo, 2010). Mix et al. (2002) surveyed the literature on quantification in infancy and early childhood and suggested that the literature provides no clear-cut evidence that infants use numbers to perform quantitative tasks. Moreover, they summarized that there is evidence that infants respond to amount of substance, rather than discrete numbers, in what had seemed to be numerical tasks. (2) Developmental trajectories similar to those with numbers (i.e., the size of the distance effect has been found to decrease over developmental time Sekuler and Mierkiewicz, 1977) have been shown in other areas (see example for the Stroop effect reported by Schiller, 1966) and seem to rely on domain-general rather than domain-specific abilities (Holloway and Ansari, 2008). During development, language may provide a medium that bridges between core domain-specific systems (Munkholm, 2001; Spelke, 2003; Platt and Spelke, 2009). Last but not least, (3) numbers are intimately associated with non-countable dimensions (e.g., size, brightness). Numerical values and physical sizes interfere with one another – the size congruity effect (Henik and Tzelgov, 1982; Tzelgov et al., 1992; Cohen Kadosh et al., 2008c) and the same apply to the relationship between numbers and brightness (Cohen Kadosh and Henik, 2006). Importantly, Lourenco and Longo (2010)

reported a size congruity effect in infants that were 9 months old. They presented convincing evidence for an intimate relationship between numerosity and size; infants who learned to expect an association between color and size of objects also expected to see a similar association between color and numerosity. Moreover, the size congruity effect is compromised in DD (Rubinsten and Henik, 2005, 2006).

This short review of the literature suggests that other factors might contribute to the development of the number sense. In particular, it is possible that the need and ability to evaluate non-countable dimensions (e.g., sizes or amounts) helped to develop or to improve the domain-specific “core knowledge” of arithmetic, which extracts numerosity of sets (Dehaene, 2009).

SIZES, AMOUNTS, AND THE NUMERICAL SYSTEM

The size congruity effect is dependent on numerical proficiency. Irrelevant numerical values will not affect relevant physical-size judgments unless the participant is proficient with the numerical system. Consequently, it was found that the size congruity effect develops with age (Rubinsten et al., 2002). In recent years this effect was employed to study proficiency with the number system and automaticity (i.e., processing even when not part of a task requirement) in numerical processing (Rubinsten et al., 2002; Cohen Kadosh et al., 2007a; Szucs and Soltesz, 2007). Recent research indicates that it involves the IPS: It was found to be deficient in a patient who suffered from a brain injury in the IPS (Ashkenazi et al., 2008) and imaging studies (fMRI) have shown that it is correlated with IPS activation (Cohen Kadosh et al., 2007a, 2008b; Szucs and Soltesz, 2007). Interestingly, other aspects of objects like brightness (Cohen Kadosh et al., 2008a), ordinal position, and time also involved the IPS (Simon et al., 2002; Walsh, 2003; Cantlon et al., 2009).

Those with DD show deficient processing in size congruity (Rubinsten and Henik, 2005, 2006) and temporary lesioning of the IPS by transcranial magnetic stimulation (TMS) produce a DD-like pattern of the size congruity effect (Cohen Kadosh et al., 2007b). Importantly, DD subjects show deficiency not only in size congruity but also in other dimensions that interact

with numbers like brightness and height (Rubinsten and Henik, 2005). Hence, it is conceivable that the basis of DD or MLD or its precursor lies with a difficulty in processing and evaluation of sizes or amounts. In a recent article, Bugden and Ansari (2011) examined the relationship between the size congruity effect and math performance in first and second grade children. They reported that size congruity did not predict math performance. This is not in line with our expectations. However, this might be due to the restriction of the range of the predictor (i.e., size congruity) or math performance or both. Alternatively, it is possible that size congruity might predict performance in older children because of its dependence on math proficiency.

Imaging data as well as behavioral results led to suggestions that “...countable and uncountable quantity...should be represented with the same kind of symbols (mental magnitudes)...to determine behaviorally important decisions” (Gelman and Gallistel, 2000), and that important computational demands of an action system (reaching, grasping) are the basis for the involvement of the parietal lobes in comparative judgment tasks (Walsh, 2003). Namely, it has been suggested that the parietal lobes reflect computational demands of the brain dorsal system involved in perception for action (Goodale et al., 1991; Goodale, 2000). However, Cantlon et al. (2009) have recently suggested that the ability to evaluate magnitudes (e.g., size) might underlie the development of the numerical system. This is in line with the general view suggested in the current proposal. Namely, the evolution of the dorsal brain system might have been dependent on the ability to compute size and size differences. A neurocognitive system that handles this aspect of cognition (evaluation of size or amount) might have been instrumental for the development of the occipito-parietal dorsal brain system (perception for action). This same system (evaluation of size or amount) helped develop or improve the numerical system.

Interestingly, recent works on perception of objects using various size and distance illusions suggested that perceived rather than retinal size modulates activation of early visual areas (i.e., v1; Murray et al., 2006; Sterzer and Rees, 2006; Fang et al., 2008). Moreover, according to Goldfarb and Tzelgov (2005), perceiving size, on the

basis of monocular distance cues, is automatic and modulates numerical processing. It is possible that size is processed very early both in terms of visual feature extraction and in terms of timing in the visual stream. This information is fed forward to the parietal lobes (and other brain structures) to serve other systems and goals (e.g., the dorsal brain system).

In a recent article, Piazza (2010) reviewed two early pre-verbal systems: the approximate number system (ANS) and the object tracking system (OTS). She suggests that children are equipped with both systems before symbolic learning takes place, each system is based on dedicated neural circuits, and each undergoes a separate developmental trajectory. Piazza concludes that the ANS rather than the OTS is crucial for the development of numerical cognition. The ANS represents numbers in an approximate fashion. However, the ANS (and OTS) involves enumeration of discrete quantities and obeys Weber’s law. The current proposal focuses on the ability to evaluate and perceive continuous and non-countable properties. Needless to say, evaluation of continuous variables is approximate by definition. Similarly, Gebuis and Gevers (2011) recently suggested that continuous visual properties, like area subtended by dot arrays, modulate performance that was earlier suggested to rely on numerosity.

A PRECURSOR OF THE NUMERICAL SYSTEM?

We suggest that routines and neural structures built for size judgments were made available to other systems (e.g., language), through evolution, due to the need to develop an exact numerical system. We have focused on the existence of non-countable representations and the ability to perceive and evaluate sizes or amounts. We suggest that the ability to perceive and evaluate sizes might be a more primitive system that was exploited, throughout the years, as the basis for the development of the number sense and numerical abilities. Whether this system was “...hi-jacked to perform judgments along a new dimension (e.g., number)” (Cantlon et al., 2009), was shaped by cultural needs (Dehaene, 2005; Dehaene and Cohen, 2007), or became accessible to the numerical system through evolution (Rozin, 1976) is not clear. But

this system might be the antecedent of the numerical system. Note that this fits in with the idea put forward by Piaget that continuous spatial extent serves as the antecedent to a child's concept of discrete numbers (Feigenson, 2007). Going back to the discussion of the OTS (Piazza, 2010), it seems that object individuation is a necessary process on the way to a discrete numerical system. Within the framework of the current proposal, it is important to find out how organisms moved from evaluation and perception of continuous non-countable properties to perception and enumeration of individual objects, or more generally, how these two abilities affected one another.

Interestingly, the visual system is characterized by a similar arrangement. Humans have two co-existing visual pathways. In addition to the primary, evolutionarily younger, geniculo-striate system there exists an evolutionarily older system – the retino-tectal pathway. These two systems have somewhat different roles but are connected and have mutual effects (Henik et al., 1994). The evolutionarily older system deals mainly with spatial aspects of vision and connects to the parietal lobes. Interestingly, the evolutionarily older system is critical in blind-sight when the primary visual system is damaged (Rafal et al., 1990). As alluded to earlier, it is quite possible that the number and the size/amount systems evolved to coexist, similar to these two visual systems.

Alternatively, it is possible that evaluation of size/amount is not based on a separate system but rather only one system exists. This could be a system that processes both numerosity and sizes or amounts. Both aspects of this system evolved together due to changing natural requirements. Namely, moving between the requirement to develop an enumeration ability under certain circumstances and the requirement to evaluate sizes (note Helmholtz's unconscious inference, which explains size constancy) under other conditions. A situation like this would create a modular system whose modules are used interchangeably (Kashtan and Alon, 2005).

In order to gain a comprehensive picture of numerical cognition, there is a need to study the ability to perceive and evaluate sizes and amounts and their relationship to the development of the numerical system.

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