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theory. It takes the form of a developmental scenario, whereby numerical competence emerges from learning "the correlation between numerosity and continuous magnitudes."

There are at least two logical flaws with this view. The first is its circularity. Capturing the correlation between numerosity and other dimensions requires representing numerosity in the first place. The authors acknowledge it and simply propose that number words would serve to trigger the emergence of numerosity. But how would number words make contact with numerosities? No answer is offered. The second and even more serious issue is that it is unclear whether continuous dimensions are sufficient to extract a representation of number, because the natural correlations between numerosity and continuous magnitudes even if most often present, are not stable in the world (see Figure 1). Sometimes numerosity could be predicted from contour area rather than occupancy, and sometimes it is the other way round. Therefore, whereas multiple cues may serve as proxies to order collections by numerosity, it is unclear how they could subserve the *estimation* of number.

To conclude, we would argue that a minimal requirement for future theoretical endeavours about numerosity processing would be to seriously consider and implement distinctions between the mechanism of numerosity extraction, the format of numerosity representation, and the decision processes that are required to perform a given task. That (some) continuous magnitudes would be extracted and combined in some weighted average to deliver a representation of number is one logical possibility. How the weights are determined without reference to numerosity remains, however, to be clarified. Yet another possibility would be that continuous magnitude information only affects late decision stages. Other scenarios are also possible, and we believe, more plausible. One is a specific, direct, numerosity extraction mechanism based on sampling the visual scene for individual elements feeding into a common magnitude representation system (see Cantlon et al. 2009b).

Perceiving numerosity from birth

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Abstract: Leibovich et al. opened up an important discussion on the nature and origins of numerosity perception. The authors rightly point out that non-numerical features of stimuli influence this ability. Despite these biases, there is evidence that from birth, humans perceive and represent numerosities, and not just non-numerical quantitative features such as item size, density, and convex hull.

Although it is impossible to simultaneously control for all continuous quantities in a single numerosity display, some studies have developed ingenious designs controlling these variables across all of the experiment's displays, as for example in Xu and Spelke's (2000) seminal study. Six-month-old infants saw first several arrays of a fixed numerosity (either 8 or 16, in different groups), varying in dot size and position. Once habituated, all infants were tested with two numerosities in alternation (8 and 16). Crucially, different aspects of stimuli were controlled in the habituation and test phases: the summed area of all dots (as well as brightness and contour length) and the array area were matched on average between the 8 and 16 habituation groups, while the density and dot size were matched between the two tested numerosities. Therefore, if infants attend to dot size or density, they will respond in the same way to test numerosities 8 and 16; whereas if infants attend to summed area or array area, the two groups will respond similarly to the test stimuli. Sensitivity to non-numerical parameters, either a single parameter or a combination of them, thus cannot explain the interaction pattern observed: In both groups, infants looked longer at the novel numerosity. This finding has been replicated by a different group (Brannon et al. 2004), using different numerical values (Xu 2003), in the auditory modality (Lipton & Spelke 2003), and the same parameter control strategy was employed to demonstrate sensitivity to numerosity at the brain level (Izard et al. 2008, Piazza et al. 2004).

Similar controls for non-numerical features were used to demonstrate newborns' sensitivity to number (Izard et al. 2009). While hearing a fixed value of numerosity (e.g., 12), newborns looked longer to arrays matched in numerosity than to non-matching arrays (e.g., 4). Because the stimuli were presented across two different modalities (auditory and visual), the newborns' response was necessarily based on an abstract property of the stimuli. Following the logic of Xu and Spelke (2000), extensive parameters were controlled in the auditory stimuli across the two groups by equating the duration, and intensive parameters across the two test numerosities in the visual modality by equating density and item size. Therefore, infants' preference for the matching stimuli could be explained only by numerosity, not by sensitivity to an abstract notion of amount, or rate. Moreover, as infants received only one numerosity in the auditory modality, they could not be responding to relative quantity ("more" or "less"). In that respect, the numerosity paradigm departed crucially from another paradigm used later (de Hevia et al. 2014), in which newborns matched two values, one small and one large, across the two dimensions of numerosity and spatial extent. Newborns are able to relate increases versus decreases of quantities at a generic level, but also to perceive numerosities, calibrated across senses.

In line with these findings, studies investigating newborns' visual perception have demonstrated that they are able to represent individual objects, at the same age as in the numerosity study. In particular, human newborns can perceive complete shapes over partial occlusion (Valenza et al. 2006), and they can both distinguish individual elements of a stimulus or group them into a holistic percept (Antell and Caron 1985, Farroni et al. 2000, Turati et al. 2013). Moreover, newborns respond differently to faces displaying direct versus averted gaze (Guellai & Streri 2011), a much finer cue than the shapes used in the numerosity experiment. Perceptual abilities to individuate items from the background and from one another likely fed into the numerosity percept evidenced by Izard et al.'s (2009) study.

Despite the common belief that numerosity perception must be more complex, and therefore a later developmental achievement, than the perception of continuous quantity, developmental studies have provided evidence that numerosity discrimination is easier and more automatic. In particular, infants show higher sensitivity to, and prefer to look at, changes in numerosity over changes in item or total surface area, when difference ratios are equated across dimensions (Brannon et al. 2004; Cordes & Brannon 2008; 2011), and even when variations in number are smaller (Libertus et al. 2014). Similarly, children show higher sensitivity to number than to density (Anobile et al. 2016b). That perception of numerosity is more automatic than other continuous quantities is true in adults too: Even without an explicit task, numerosity of visual arrays is processed faster than other continuous features of those arrays (Park et al. 2016b). In this context, it is important to note that although Stroop studies on adults indicate that continuous quantities interfere with number perception, much of the behavioral and neuroscientific evidence cited by Leibovich et al. is based on interference paradigms in which non-numerical quantities varied by considerably larger ratios (and, thus, likely had higher perceptual discriminability and salience) than numerosity.

At the brain level, areas in the intraparietal sulcus respond to numerosity, and not simply to non-numerical cues. In particular, Eger et al. (2009) used intraparietal sulcus activations to train a classifier to discriminate between patterns evoked by different numerosities across which item size was equated and found that this classifier generalized without accuracy loss to patterns evoked by numerosities across which total surface area was equated (and vice versa). Numerosity was also decodable from the intraparietal sulcus when low-level factors such as contrast energy were equated (Castaldi et al. 2016). Finally, in the right superior parietal lobe Harvey et al. (2013) observed an orderly topographical structure of numerosity responses, correlated across stimulus sets implementing different controls. Although the same region also responds to object size (Harvey et al. 2015), the tuning curves and map organization differ, thus highlighting the specificity of the numerosity response.

In summary, the literature brings uncontroversial evidence that humans perceive and represent numerosity from birth on. As pointed out by Leibovich et al., the literature also brings uncontroversial evidence that numerosity perception is imperfect, often subject to the influence of non-numerical aspects of stimuli. These phenomena are fascinating, as they open up a new research agenda – if perception of numerosity relies on an imperfect algorithm, we now need to crack up its functioning.

Multitudes are adaptable magnitudes in the estimation of number

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Abstract: Visual number comparison does not require participants to choose a unit, whereas units are fundamental to the definition of number. Studies using magnitude estimation rather than comparison show that number perception is compressed dramatically past about 20 units. Even estimates of 5–20 items are increasingly susceptible to effects of visual adaptation, suggesting a rather narrow range in which subitizing-like categorization processes blend into greater reliance on adaptable magnitude information.

When people perceive a collection as having an amount, do they assign a conceptual category (number) to something that is experienced as a multitude of units, or is that conceptualization dependent on language? In Book 7 of Euclid's *Elements* (300 BC/1956), Euclid famously defined a number as "a multitude of units" after having defined a unit, quite wonderfully, as "that by virtue of which each of the things that exist is called one" (p. 277). Leibovich et al. propose that whether nervous systems treat perceptual number as a multitude rather than a magnitude may be unknowable because perceived number cannot be isolated from all confounding perceptual continuous magnitudes that are typically correlated with number. But multiple information-processing systems in perception might work together to help obviate this concern. Here I consider how the fragile boundary between magnitudes and multitudes might be manifest in numerosity estimation.

Unlike most perceptual magnitudes (loudness, area, brightness), numerosity has a built in unit. To compare the numbers of two collections is to try to identify a relative quantity of units. For small collections of two or three, special geometrical or attention processes may differentiate categories, but for large numbers, clearly any estimate must be an approximation. Is it simply a sensed magnitude? There is evidence that even a collection as small as five fails to form a discriminable numeric category in human adults in the absence of linguistic labels (Gordon 2004).

For some, the adaptability of visually perceived number is to strongly suggest that large visual number is estimated based on correlated features (Durgin 1995). How else could 200 dots appear perceptually equivalent to 400 dots? It could not be that some of the dots are missing. Rather, some visual property is clearly being adapted, and locally rescaled, and that property seems to act like a continuous magnitude (like brightness, loudness, etc.). Durgin argued that effects of adaptation produced multiple visual consequences including the underestimation of apparent numerosity – which was most pronounced for high numbers (in the hundreds), but also changes in perceived spacing or distribution. Adaptation, like number comparison, provides no obvious way to unconfound number, except insofar as adaptation fails (i.e., true number triumphs).

Number comparisons may be thought of as comparing several visual magnitudes correlated with numerosity (including area, Allik & Tuulmets [1991], and density). Whereas Anobile et al. (2014) sought to distinguish between number perception and density perception using differential Weber fractions, as Leibovich et al. point out, even distinguishing two distinct sources of judgment does not show that either one of them is number itself.

Still, the existence of multiple sources of information relevant to estimating numbers does not show that number perception does not occur. Having multiple sources of information about depth that get combined into a common perceptual estimate does not mean that we do not perceive depth, but it is hard to infer the information content of perceptual experience solely from discriminations tasks or categorization tasks.

An alternative approach to studying number with humans is to use magnitude estimation rather than magnitude discrimination. That is, human participants who have a linguistic number system can estimate how many units are present, just as they can estimate other psychophysical properties. Studies by Krueger (1972) and by Kaufman et al. (1949) have shown that dot collections as high as 200 dots are grossly underestimated, suggesting that "number" is (under) estimated rather than sensed for numbers of this magnitude. Perhaps this is just a translation problem of converting perceptions into words or maybe approximate "number" perception is just an adaptable continuous magnitude that humans conceptualize as being composed of units.

Alex Huk and I (Durgin 2016; Huk & Durgin 1996) tested how density adaptation affects number estimation. Participants who were adapted to dense texture to one side of fixation were briefly shown either one field of dots on one side or the other, or two fields of dots (one on each side). When only one field was flashed, they reported its apparent numerosity; when both fields flashed, they were to indicate which side appeared more numerous. The effect of adaptation on numerosity comparison was stronger as numerosity increased, and a similar pattern emerged for numerosity estimation.

The estimation data are shown in Figure 1. Number estimates were unaffected for 5 dots. But for more numerous collections (40 dots or more), estimates were about 25% lower in retinotopic regions adapted to dense (high numerosity) random dots fields than in unadapted regions. The average estimate for 256 actual dots, for example, was 154 in the unadapted region, and only 117 in the adapted region. Significantly, the numerosity estimation functions shown here in log-log space seem to bend significantly between 20 and 40 dots.

model and look forward to seeing what future studies will bring.

NOTES

1. Tali Leibovich and Naama Katzin contributed equally to this work.

2. Maayan Harel was not available to contribute to the Response article and did not participate in writing it. Moti Salti was not involved in writing the target article, but contributed to the Response article and participated in writing it.

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[The letters “a” and “r” before author’s initials stand for target article and response references, respectively]

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