Numbers in Action

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Abstract
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Abstract

To understand the number sense, we need to understand its function. We argue that numerosity estimation is fundamental not only for perception, but also preparation and control of action. We outline experiments that link numerosity estimation with action, pointing to a generalized numerosity system that serves both perception and action preparation.

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Clarke and Beck do an impressive job reviewing, and largely refuting, objections for the existence of a number sense, such as congruency, confounds, and imprecision. Arguments of this type are not new. For example, imprecision is at the basis of the well-known philosophical "problem of the speckled hen," presented by Gilbert Ryle to Ayer (1940): "Consider the sense datum yielded by a single glance of a speckled hen: how many speckles does the datum comprise?." That humans cannot enumerate the number of speckles was considered a major challenge to prevailing philosophical theories about "given, direct experiences." Why did Ryle choose number for his challenge, rather than the color, height, or weight of the hen, all equally impossible to judge with great precision? Clearly, our inability to enumerate a discrete number of specks makes the point more intuitively. Perhaps, it is the digital nature of numbers, which implies a discrete and precise description; or perhaps because we have multiple ways of measuring number, including rapid but approximate estimation (approximate number system [ANS]), systematic, and errorless serial counting, as well as exploiting grouping strategies (Anobile, Castaldi, Moscoso, Burr, & Arrighi, 2020a; Starkey & McCandliss, 2014). We can, therefore, internally check our rough numerosity estimation, readily betraying its imprecision: checking analog attributes requires instruments such as photometers, tape-measures, or scales. However, the fact that numerosity can be gaged in various ways, with variable precision, does not refute the existence of a number sense. On the contrary, that number estimation is imprecise and essentially noise-limited is further evidence that it is a sensory system. Ayer did not have the concept of noise-limitation in 1940 (introduced a few years later to psychology and physiology), but correctly anticipated that although the hen does have a definite number of speckles, the sense datum has only an imprecise guess: essentially, the approximate number system.

Perhaps, the more pressing question is not so much whether a number sense exists, or what class of numbers it encodes, but what purpose does it serve? Has it evolved primarily for estimating the number of speckles on a hen? – or the number of times the hen pecks? – or to help control and monitor the hen's own pecking behavior? It is likely that all are relevant, but the role of perception in action has traditionally been underrated (Goodale, 2014). We argue that numerosity perception is intrinsically linked with action. This is particularly clear in complex tasks such as bullet routines, music production, and the extraordinary waggle dance of bees. But action and number are strongly linked in most movement tasks, such as walking, talking, or eating. It is, therefore, perhaps not surprising that neurons have been identified in monkey cortex that are selective to the number of actions the monkey makes, either turns or pushes (Sawamura, Shima, & Tanji, 2002).

We have used adaptation techniques to reveal a strong link between action and number estimation in humans (Anobile, Arrighi, Togoli, & Burr, 2016). Participants tapped in mid-air with their dominant hand, either very quickly, or around one tap per second. Fast tapping caused robust underestimation of the numerosity of subsequently presented stimuli, and slow tapping caused robust overestimation (see Fig. 1).

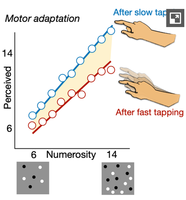

Figure 1. Effects of motor adaptation on perceived numerosity. Average perceived numerosity after a few seconds of slow (blue) or fast mid-air tapping (red), as a function of physical numerosity.

The effects were large, around 25%, and equally strong for estimating the number of items in a spatial array as for the number of events in a temporal sequence. This reinforces evidence of a generalized sense of number, spanning space, time, and sensory modality (Arrighi, Togoli, & Burr, 2014), and shows that this general sense is strongly linked to action. Importantly, adaptation (either to tapping or to sequential stimuli) does not generalize over the entire visual field but is confined to the immediate spatial vicinity where the hand had tapped or the stimuli presented (irrespective of the tapping hand). This demonstrates a spatially specific perceptual origin, rather than adaptation or a more general cognitive effect (such as internal counting). Interestingly, the spatial selectivity (for tactile sequences) is as strong in the congenitally blind as in sighted participants (Togoli, Crollen, Arrighi, & Collignon, 2020), showing that visual experience is unnecessary.

The effect of adapting to hand-tapping on perception was not limited to numerosity, but observed also with duration and spatial location estimates (Anobile, Domenici, Togoli, Burr, & Arrighi, 2020b; Petrizzo, Anobile, & Arrighi, 2020). This again is to be expected, given the close links between space, time, and number (Walsh, 2003), and their clear role in action (especially, time).

Other links between action and numerosity perception have been reported with saccadic eye movements. Observers can saccade very quickly toward the more numerous of two arrays, implying a link between action and numerosity systems through dedicated pre-attentive mechanisms (Castaldi, Burr, Turi, & Binda, 2020). At the time of saccades, numerosities of spatial arrays are grossly underestimated, paralleling the effects on temporal duration and spatial extent (Burr, Ross, Binda, & Morrone, 2010). Saccades also affect symbolic numbers: Participants underestimate the results of additions and subtractions when digits are presented at the time of saccades (Binda, Morrone, & Bremmer, 2012). Pupil size is modulated by perceived numerosity, even in the absence of a psychophysical task (Castaldi, Pomè, Cicchini, Burr, & Binda, 2021).

All these results reinforce the existence of an approximate number system in humans, and show that this system encodes numerosity in a generalized manner, across space and time and sensory modality, for use in both perception and action (Anobile, Arrighi, Castaldi, & Burr, 2021). As perception and action are strongly linked in everyday life, the emergence of a sensorimotor mechanism would seem to be a parsimonious and evolutionary useful strategy. For these functions, natural numbers (which include the fascinating case of zero; Nieder, 2016) are sufficient, but we cannot exclude the possibility that the same system encodes rational numbers such as fractions when required.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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