Research Focus

The equality of quantity

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Do disparate dimensions of magnitude share an underlying mental representation? Two recent papers offer suggestive evidence that participants' discrimination thresholds are identical across domains. Brannon, Lutz and Cordes showed that six-month-old infants' area discriminations match their number discriminations. VanMarle and Wynn demonstrated the same pattern for six-month-olds' discrimination of temporal duration. These parallels across infants' responses to number, area and time raise questions about the fundamental nature of quantity processing.

Introduction

Adults, infants and animals represent number, area and time. We approximate the number of items in a set, the size or spatial extent of a stimulus and the duration of an event, and we use these quantifications to guide our learning and behavior. Intriguingly, our concepts of how many, how much and how long seem intertwined, at least at the metaphorical level. We refer to 'starting back at square one' (using spatial extent to refer to time), talk about an expensive item 'setting us back' (using spatial extent to refer to number) and 'count down' to a big event (using number to refer to time). Does this cross-referencing merely reflect human rhetorical flourish or does it belie a more fundamental connection between thinking about number, area and time? Two recent studies of infants offer exciting new evidence.

Analog number representations

Setting the stage for this new work is research showing that adults and infants represent number in an analog format. When comparing numerical values, adults' speed and accuracy are determined by the ratio between quantities rather than by absolute value [1]. This means that the threshold for noticing a numerical change in a non-symbolic quantity is constant across changes in modality and changes in numerical scale. In adults, this threshold is ~7:8 [2].

Infants rely on the same system of analog number representations, albeit with less precision. Six-month-olds discriminate arrays of dots that differ by at least a 1:2 ratio, but fail with more difficult ratios (e.g. they succeed with 8 versus 16 but fail with 8 versus 12) [3]. The same pattern obtains in audition [4]. Interestingly, the precision of numerical representations sharpens over development. Eight- to nine-month-olds succeed with the 2:3 ratios with which six-month-olds fail, in both the visual and auditory domains. Thus, our approximate number representations exhibit error that increases in constant proportion to the target number, and that proportion shrinks over development.

Parallels in thresholds

A pair of developmental studies now suggests that these number representations converge with representations of area and time. First, Brannon and colleagues investigated infants' representations of the area of a visual stimulus [5]. Six-month-olds were habituated to either a single small or a single large cartoon face, and then were tested with alternating trials of both a small and a large face. The two faces differed by a 1:4, 1:3, 1:2 or 2:3 ratio in total area. Infants discriminated all but the 2:3 change. Note that the 1:2 threshold obtained here for area is identical to that obtained in previous studies that tested number with the same age group.

VanMarle and Wynn used a similar method to study infants' temporal discrimination [6]. Six-month-olds were habituated to a puppet that emitted a tone of either 2 s or 4 s duration (looking time was recorded after the tone had stopped). When tested with alternating trials of both 2 s and 4 s, infants looked longer on trials with the novel duration. However, when the tones were changed to 3 s versus 4.5 s, infants showed no such preference. The authors also showed that infants discriminated 0.5 s from 1 s, but not 0.67 s from 1 s. Crucially, then, infants' threshold for duration discrimination remains constant over changes in scale and also matches the threshold for number discrimination.

That six-month-old infants detect a 1:2 change but fail to detect a 2:3 change in number, area and duration is consistent with a view that all three dimensions rely on a shared mental mechanism.

In what sense shared?

The possibility of unifying dimensions of quantity into a common format has historical precedent in the work of Piaget, who believed that children's concept of discrete number was borne from a concept of continuous spatial extent. This theory also finds support in proposed models that represent number and time, or number, space and time, via shared machinery [7,8]. According to the strongest view, a single mental device might represent all three dimensions. There are other possibilities. Number, area and time might share a representational format that is output by separate devices – a case of nature applying the same solution to the common problem of representing large variation in the scale of external stimuli. Also, if a shared decision procedure operates on these representations, performance

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Table 1. Infants' successes and failures at discriminating various dimensions of quantity

Dimension tested	Stimulus type	Age	Success ratio	Failure ratio
Duration	Tones emitted from a toy	6 months [6]	1:2	2:3
		10 months [10]	2:3	3:4
Area of a single object [5]	2D cartoon face	6 months	1:4, 1:3, 1:2	2:3
Summed area of multiple objects [11]	Hidden pieces of food (sets of three or fewer)	10–12 months	1:2, 2:3	N/A
	Hidden pieces of food (sets of four or more)	10–12 months	Unknown	1:4, 1:2, 3:4
Volume [12]	Liquid in cylinder	6 months	1:3	Unknown
Length [13]	Wooden dowel	6 months	1:2	Unknown
Distance [14]	Location of a hidden object	6 months	2:3	Unknown
Summed perimeter of multiple objects [15]	2D shapes	6–8 months	1:2	Unknown
Area or volume of a substance (K. vanMarle, unpublished)	Pours of cereal	10–12 months	1:4	1:2
Number (sets of three or fewer)	3D toy objects [16]	5–7 months	1:2, 2:3	N/A
	Auditory tones [4]	6 months	Unknown	1:2, 2:3
	Events [17]	6 months	Unknown	1:2
Number (sets of four or more)	2D shapes [3]	6 months	1:2	2:3
	Auditory tones [4]	6 months	1:2	2:3
		9 months	2:3	4:5
	Events [17]	6 months	1:2	2:3
		9 months	2:3	Unknown

might be limited by this common comparison process rather than by common representational contents.

Brannon *et al.* and vanMarle and Wynn provide tantalizing data that help narrow this possibility space. Several avenues for future research also seem particularly promising. First, if number, area and time are subserved by the same mechanism, one should expect parallel rates of change in their acuity over development. As children become able to detect finer differences in number, they should also show this ability for differences in spatial extent and duration. At present, a detailed portrait of how acuity changes in any of these dimensions is lacking. Nothing is known of acuity before six months or how acuity sharpens from 2:3 at nine months to the adult level of 7:8. Determining whether the discrimination functions for all three dimensions superimpose throughout development will be key to understanding their relationship.

Second, the range of values with which number, area and time have been tested remains relatively small. The classic psychophysical work that produced intensity functions for directly perceived dimensions, such as loudness, brightness and temperature, rested on a broad base of tested values. These revealed that the functions for some of these dimensions overlapped at values of low intensity, but diverged at higher intensity. To determine whether the relationship between number, area and time is one of identity or merely similarity will require extending their psychophysical functions.

Third, a general representation of quantity would encompass many other measures, including volume, length, distance and perimeter. More research is needed to map acuity for these dimensions so it can be established whether these too share the same discrimination thresholds. Existing results in cognitive development start to address this issue. Table 1 lists various quantity dimensions and the ratios infants have successfully discriminated. The table reveals that, for many dimensions, six-month-olds succeed with ratio changes of 1:2 and nine-month-olds succeed with ratio changes of 2:3. Yet there are also inconsistencies. Infants' discrimination threshold for nonsolid substances is much higher than for other stimuli, and discrimination for the number and area of sets containing three or fewer objects is lower than that for larger sets. It remains to be seen whether these discontinuities pose serious problems for the theory of a common representational mechanism.

Finally, the theory that diverse representations of quantity share a common mechanism predicts that deficits in processing one dimension should by accompanied by deficits in processing others. This prediction recently received empirical support: patients who have hemispatial neglect show systematic error not only when performing a spatial bisection task, but also when performing a numerical bisection task [9]. Further neuropsychological results such as these could provide another important source of evidence for evaluating the claim of shared quantity representations.

Until these avenues for future research are pursued, the results of Brannon *et al.* and vanMarle and Wynn provide an exciting teaser for discoveries that are still to be made concerning the nature of quantity representations.

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The default self: feeling good or being right?

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The medial prefrontal cortex exhibits a higher resting metabolic rate than many other brain regions. This physiological default mode might support a psychological default state of chronic self-evaluation that helps people consider their strengths and weaknesses when planning future actions. However, a recent imaging study that relates medial prefrontal cortex activity to self-evaluation raises new questions about whether the psychological default mode of self-evaluation is best characterized by accurate self-evaluations or by feeling good about yourself.

Introduction

Neural investigations of self suggest an intriguing relationship between the resting physiology and the psychological function of the medial prefrontal cortex [1–5]. The medial prefrontal cortex has a higher level of baseline metabolism in comparison with many other brain regions [5]. The baseline physiological difference in the medial prefrontal cortex has been theorized to reflect a baseline psychological characteristic of the mind when it is not otherwise engaged in a specific task. The increased resting metabolism of the medial prefrontal cortex might support a generalized, automatic evaluation of self [5]. This default psychological mode promotes the consideration of one's strengths and weaknesses so that future actions can be planned in light of these qualities. The association between self-evaluation and medial prefrontal cortex has been supported primarily by studies that compare judgments about the self with judgments about other social objects or low-level characteristics of stimuli (e.g. a self-reference paradigm) [1–4]. In these studies, self-judgments (e.g. descriptiveness of personality traits) are associated with changes in medial prefrontal activity. A recent fMRI study by Moran *et al.* extends this research by investigating whether medial prefrontal cortex is associated with cognitive aspects or emotional aspects of self-evaluation [6]. In other words, is medial prefrontal cortex recruited for evaluations of the self because those evaluations draw on a particular cognitive process or because those evaluations involve emotional biases that paint the self in an unrealistically positive manner?

Medial prefrontal cortex: a default mode of cognitive self-evaluation

Moran *et al.* recently examined the neural underpinnings of cognitive and emotional processing in relation to the self by scanning participants while they used a four-point scale (from 1 = not at all like me, to 4 = very much like me) to rate themselves on a series of positive (e.g. sincere) and negative (e.g. liar) personality traits [6]. There were three main findings. First, increases in medial prefrontal cortex and posterior cingulate activity over time were related to increases in self-description ratings. Second, response latencies were not associated with medial prefrontal cortex, which suggests that this region does not simply index time spent on the task. Third, medial prefrontal cortex and posterior cingulate activity were related to cognitive processing (high versus low self-description ratings), whereas activity in the ventral anterior cingulate was related to emotional processing (positive versus negative traits), particularly for highly self-descriptive traits (Figure 1a). These findings refine our understanding of medial prefrontal activity and self-evaluation [1–4]. This area is recruited for cognitive aspects of self-evaluation, such as judging the descriptiveness of personality traits, and is not recruited for emotional aspects of self-evaluation, such as favoring positive information over negative information.

The 'psychological' default mode of self-evaluation

The study by Moran *et al.* [6] furthers our understanding of the default mode of self-evaluation associated with medial prefrontal cortex, but it also presents a puzzle. Is the normative, default mode of self-evaluation characterized by accurate information gathering or by a biased search for flattering information? As stated earlier, the increased resting metabolism of the medial prefrontal cortex is theorized to support a default psychological mode of self-evaluation that provides chronic, generalized updates on

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