More is different

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Throughout history, humans have had to make decisions based on numerical comparisons of competing choices. Does this part of the forest yield more fruit than the other? What route leads to more or fewer violent encounters? Which shop has better deals? Although a computer with unlimited capacity could simply compute precise averages, humans often (by necessity) employ other methods. In a new set of experiments, Spitzer et al. asked people to decide which of two streams of numbers had a higher average value. Doing so, they provide new and exciting insights into the strategies humans employ to compare numerical magnitudes.

The study of the mental representation of numbers and magnitudes has a long and storied history in psychology. For instance, in an influential study, Antoine Bechara and colleagues examined how humans chose to select cards from two 'decks' with differing expected returns. They showed that both conscious and unconscious processes were at play as subjects assessed the quality of the decks, and that selective brain lesions could impact on different aspects of the decision strategy.

One particularly influential concept is that of the *mental number line* – our internal representation of numbers and numerical magnitudes, which does not necessarily align with the mathematical number line. A classic distortion of this number line is relatively easy to experience subjectively (or elicit in unwary friends or family). Put two markers on a table about two feet apart. Now, imagine the left marker represents the number 1 and the right marker represents the number 10. Where (and respond quickly!) is the number 5? Most people will point somewhere very close to the middle of the interval. Now repeat this experiment, but instead imagine the left marker to represent one thousand and the right marker one billion. Where (again, respond quickly!) does the number one million fall? Most people will intuitively choose a location somewhere in the middle or slightly to the left of the middle – until deliberative reflection kicks in and you realize that one million is at the extreme left hand side of this artificial 'number line.'

In a series of studies published in 2008, cognitive psychologist Stanislas Dehaene showed that individuals from western civilisations tend to scale small numbers linearly but large numbers logarithmically, whereas members of an Amazonian tribe always showed logarithmic scaling, independently of number magnitude. This distinction may arise due to cultural and educational differences in the importance of (small) numerical values. Such patterns are examples of one of the most well established findings in psychophysics: The Weber-Fechner law, which states that the subjective difference between any set of stimuli decreases as the absolute magnitude (volume, length, brightness) increases. However, an exciting new study by Bernhard Spitzer and colleagues published in Nature Human Behaviour suggests that things may not always be so simple.

In this study, participants observed a sequential stream of numbers that ranged from 1 to 6 and belonged to two categories, indicated by the colour of the number (e.g. green and red). At the end of the number stream presentation, subjects were asked to judge which of the two categories had the higher numerical average. A perfect observer, such as a computer, would simply update the average with each subsequent number and make the correct decision. However, doing so is extremely hard for humans and, unsurprisingly, the participants' performance was not perfect. Interestingly, Spitzer et al. showed that it was imperfect in very specific and fascinating ways.

Using a computational model, the authors demonstrated that humans treat numbers from 1 to 6 differently. First, people showed greater responses to 'outliers,' such as 1 and 6. These far ends of the number line had an outsized influence on the decision of which category had the highest average - a phenomenon Spitzer et al. dubbed 'anti-compression.' Secondly, and most intriguingly, people showed a consistent bias towards *larger* values (5 and 6). Converging evidence for both the bias and anti-compression effects came from neuroimaging data in the form of electro-encephalographic recordings. Not only were the neural responses more pronounced for larger numbers (suggesting greater 'importance' during processing), but the patterns of activity were *more dissimilar* between two larger numbers (like 5 and 6) than between two smaller numbers (like 2 and 3). This is precisely the opposite of what would be expected under Weber-Fechner style laws described above. These patterns were observed regardless of the mode of presentation (alphanumeric symbols ('5'), groups of dots or spoken numbers).

At first, this may seem like (yet) another example of our human imperfections. However, Spitzer et al. show that the anti-compression effect, which leads to the overweighting of numerical outliers, is actually optimal (i.e. results in higher accuracy) under conditions of noise or imperfect performance. Noise can enter through the 'leakiness' of human memory. The fact that, unlike computers, we have imperfect memories of the number stream makes it so that 'biased' integration (overweighting large numbers) is actually a better strategy. In other words, given that humans are imperfect at integrating numbers, they nonetheless use a strategy that is optimal *given their imperfections*. The overweighting of outliers was shown to be even larger under more complex variations of the task, suggesting that humans can flexibly adapt the optimal strategy to their own limitations.

Several decades ago, physicist Philip Anderson coined the phrase 'More is different,' to sum up his view that new laws and regularities are needed when describing increasingly complex systems. The findings from Spitzer et al. provide an apt parallel in an entirely different realm, as they provide compelling evidence that new mechanisms are needed to adequately describe cognitive processes concerning (larger) numbers. Their findings open up a range of exciting questions for future work. Does the noise-optimal integration strategy arise during development (by learning it is better), or is it an innate feature? Is it universal across cultures? In any case, the lesson of the study is clear: humans may not be optimal, but we're very good at being suboptimal.

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