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The role of "Prominent Numbers" in open numerical judgment: Strained decision makers choose from a limited set of accessible numbers[☆]

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ABSTRACT

Numerate adults can represent an infinite array of integers. When a judgment requires them to "pick a number," how do they select one to represent the abstract signal in mind? Drawing from research on the cognitive psychology of number representation, we conjecture that judges who operate primarily in decimal systems simplify by initially selecting from a set of chronically accessible "Prominent Numbers" defined as the powers of ten, their doubles, and their halves [… 5, 10, 20, 50, 100, 200…]; then, when willing and able, refining from there. A sample of 3 billion stock trades reveals that traders' decisions reflect Prominent-Number clustering (Study 1) and a "natural experiment" reveals more clustering in rushed trading conditions (Study 2). Three sets of subsequent studies provide evidence consistent with an accessibility-based account of Prominent-Number usage: Experiments show that judges rely more on Prominent Numbers when they are induced to rush rather than take their time (Studies 3a and 3b), and when they are under high versus low cognitive load (Studies 4a, 4b, and 4c); and a final correlational study shows that Prominent-Number clustering is more apparent for judgments that require judges to scan a wider range of plausible values (Study 5). This work underscores the need to differentiate between Round Numbers and Prominent Numbers, and between representational properties of graininess and accessibility, in numerical judgment.

1. Introduction

Judgments and decisions often require the selection of a single number. An investor decides how many shares of stock to buy. A potential homebuyer predicts how much a kitchen renovation might cost. A negotiator in a fast-paced bargaining session determines the value of a newly-introduced side issue. Numerate adults have the capacity to represent an infinite array of integers. When they are asked to "pick a number, any number," how do they arrive at a specific representation of the abstract signal they have in mind?

A long line of research on anchoring-and-adjustment indicates that people can often "arrive at a reasonable estimate by tinkering with a value they know is wrong" (Epley & Gilovich, 2001, p. 391). But, perhaps just as often, the judgment at hand does not systematically activate a memory-based internal anchor, nor does it occur in the context of an informative external anchor.[1] In other words, for many judgments, judges may not have an obvious wrong value to "tinker with." A different model may be needed to understand this class of judgments that occur when neither memory nor the environment provides a ready starting place from which to adjust. We refer to such judgments as *open numerical judgments*. Despite—or possibly because of—longstanding interest in the anchoring bias, little attention has been paid to this class of unanchored judgments (cf. Stewart, Chater, & Brown, 2006). Our central aim in the current work is to examine a potential shortcut that people may spontaneously employ to simplify open numerical judgments.

We propose here that people simplify open numerical judgments by initially considering a limited set of chronically accessible numbers. Satisficing in this judgment—that is, accepting that the offered judgment may represent a relatively coarse approximation of the signal in mind—would involve considering only the most-limited set of highly accessible numbers. In contrast, given the opportunity and willingness to produce a more precise approximation, increased deliberation would involve considering more densely populated sets of decreasingly

☆ Data files, code, and original materials are available on the *Open Science Framework* at https://osf.io/kfb84/.

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[1] Implausible values can also affect numerical judgments (Chapman & Johnson, 2002; Tversky & Kahneman, 1974), but they do so by increasing the accessibility of consistent information, not by introducing a starting point (Epley, 2004; Mussweiler & Strack, 1999).

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accessible numbers. This outline of an accessibility-based model builds from the idea that people have more detailed representations of some numbers than others (Dehaene & Mehler, 1992) and that a logarithmic function provides a good description of the mental space in which people represent numbers (Banks & Coleman, 1981; Dehaene, 2001, 2003, 2007; Nieder & Miller, 2003; Piazza, Izard, Pinel, Le Bihan, & Dehaene, 2004).

Our conjecture is that, for people who primarily operate in a decimal (i.e., base-10) system of numbers, the chronically accessible set of numbers that they initially scan, and thus disproportionately rely on, is defined in theoretical work on "the prominence structure of the decimal system" (Albers & Albers, 1983; also Albers, 1997, 2001). Specifically, the "Prominent Number" set under consideration includes the powers of ten […10; 100; 1000…], their doubles […20; 200; 2000…], and their halves […5; 50; 500…]. Formally, this sequence […5; 10; 20; 50; 100; 200; 500; 1000; 2000…] can be represented as $n10^i$, where i is any integer and n is ½, 1, or 2. Albers and colleagues' treatment of these numbers in decision making focused on the convenient mathematical property that all integers can be constructed as a sum of non-repeated combinations of the Prominent Numbers using coefficients -1, 0, or $+1$. For example, $1400 = 1000 + (1 * 500) + (0 * 200) + (-1 * 100)$. Our treatment, in contrast, emphasizes the psychological (i.e., representational) properties of the numbers (Dehaene & Mehler, 1992), properties that may in fact lead people to rely disproportionately on the set when making open numerical judgments.

We began developing this model as a way to understand our initial observation (presented in Study 1) that stock trade quantities cluster disproportionately on the Prominent Numbers. Previous researchers have observed that certain numbers, including 10, 20, and 50, appear disproportionately in written language (Dehaene & Mehler, 1992; Jansen & Pollmann, 2001), visual ratio estimations (Baird, Lewis, & Romer, 1970), hypothetical willingness-to-pay estimates (Whynes, Philips, & Frew, 2005), and guesses about what numbers other people would select within a given range (Baird & Noma, 1975). They also appear to feature as common rounding values in heuristic-based decision processes (Albers, 2001; Brandstätter, Gigerenzer, & Hertwig, 2006). However, there is little clarity about whether these disparate observations identify the same, separate, or partially overlapping phenomena; and none of the accompanying accounts address open numerical judgments in general. As we sought to better understand our initial empirical result, and to try to understand how these various phenomena may or may not relate to it, we identified this as an opportunity to produce a preliminary sketch of a general model of open numerical judgments.

We first review studies from cognitive and social psychology that motivate our accessibility-based model and the specific Prominent-Number conjecture within that model. We then present seven studies that assess the potential usefulness of the proposal by testing two predicted implications for open numerical judgments. The first implication is that distributions of open numerical judgments should disproportionately cluster on the Prominent Numbers. Even if only a small proportion of a large sample of judges terminates the search after considering only the most-accessible numbers, then more judgments than expected by chance would end on one of the Prominent Numbers (more so, even, than on other Round Numbers in the vicinity). The second implication is that Prominent-Number clustering should be more apparent under conditions that favor the use of highly accessible concepts. Thus, when judges cannot or will not invest additional cognitive effort in refining their judgments, or when the judgment itself imposes a greater cognitive burden by requiring the judge to scan a wider array of plausible values, Prominent-Number clustering should increase.

1.1. From 'at-large scanning' to 'preferential representation'

Consider the dilemma of producing a numerical judgment on the fly with no accessible anchor from which to adjust. How might one proceed? For illustration, one possibility is that the judge mentally scans the full number line to find a reasonable match to the abstract signal in mind. But, without an anchor to start from, where would the judge start? At 1 and move up? At the highest number she can think of (*1 billion*? *1 trillion*?) and move down? At a random number somewhere in between? Such an account is obviously unrealistic. It would be wildly inefficient from a cognitive standpoint. From a behavioral standpoint, it would probably be mind-numbingly slow.

More to the point, an at-large scanning process is not consistent with a great deal of work on how people use and represent numbers. Research from both cognitive and social psychology has demonstrated that not all numbers are represented equally (Dehaene & Mehler, 1992; see also Schelling, 1960). Thus, at-large scanning is not a likely candidate for how open numerical judgments actually proceed. It stands to reason that open numerical judgment might be simplified through the preferential representation of certain numbers. For intuition, consider an interactive digital map. When zoomed way out, the map shows only some of the major cities. Other cities do not cease to exist, but they are not represented until one zooms in. For example, when we looked at a map of Spain while zoomed out, the edges of the map showed the tip of Maine and the west coast of India, and only the cities of Madrid and Barcelona were visible within Spain. Zooming in one level restricted the range, now framed by the Atlantic Ocean in the west and Turkey to the east, and brought more cities into view. Seville, Granada, Málaga, and Valencia were now visible alongside Madrid and Barcelona. At one more level of zoom, less Atlantic Ocean was visible to the west and the map onlyextended to Italy in the east, and nearly 30 cities become visible within Spain.[2] With respect to the number line, we compare the Prominent Numbers to the major cities. When people are "zoomed way out" (i.e., in the initial step of an open numerical judgment), we suggest that the major units they see are some subset of […50; 100; 200; 500; 1000; 2000…]. The numbers in between can be "seen" (i.e., become more accessible) as people "zoom in" (i.e., refine), but this requires cognitive effort. The potential efficiency gain over at-large scanning is obvious.

1.1.1. Detailed representation and accessibility

The internal representation of numbers is compressive and akin to Fechner's law, that is, it is more detailed for small numbers than for large ones. (Dehaene & Mehler, 1992, p. 19).

Consistent with the intuition of commonly used language, cognitive science suggests that numerate adults mentally organize quantities along some continuum, or "mental number line" (Dehaene, Bossini, & Giraux, 1993; Dotan & Dehaene, 2016). The number line in people's heads, however, may be quite different from the version that hangs on the walls of elementary school classrooms. The latter is linear in its scaling, representing every integer with equal detail. The former, according to both behavioral and neuroscience studies, represents certain numbers with more detail than others, with the numerical distance between the preferentially-represented values getting further and further apart as magnitude increases (Dotan & Dehaene, 2016). In the same way that people perceive the difference between two relatively quiet sounds to be greater than the equivalent difference between two relatively louder sounds (i.e., the "Weber-Fechner Law"), people also perceive the difference between two relatively small numbers to be greater than the equivalent distance between two relatively large numbers (Krueger, 1989; Shepard, Kilpatric, & Cunningham, 1975). While there is ongoing debate about the most precise way to mathematically describe this mental compression, a logarithmic function provides a good account (Banks & Coleman, 1981; Dehaene, 2001,

[2] As we were researching this example on Google Maps, we could not help but notice that the unit Google scales to moves successively from 1000 mi., 500 mi., 200 mi., 100 mi., 50 mi., 20 mi., 10 mi., 5 mi., 2 mi., 1 mi., 2000 ft., 1000 ft., … down to 20 ft.