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OUTLOOK

Even bees know zero is less than one

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Summary

Across three elegant experiments, Howard, Avarguès-Weber, Garcia, Greentree, & Dyer (2018) demonstrate that honey bees spontaneously generalize an ordinal rule to empty sets, treating zero as less than other whole numbers. Their findings provide strong evidence that bees have a nonsymbolic concept of zero similar to that found in monkeys and human children, suggesting that this capacity may have important evolutionary significance.

Keywords Zero · Empty set · Numerical cognition · Honey bees

Is there something special about zero? It has long been thought that zero is unique from other numbers. Over human history, the first recorded instance of the symbol zero used to represent quantity (or the absence of quantity) was a relatively late occurrence relative to that of other numerical concepts (Nieder, 2016). This protracted acquisition of zero over human history also mirrors the delayed acquisition of zero in human development: Evidence suggests that preschoolers' understanding of symbols for zero (i.e., the word "zero"; Arabic numeral) falls way behind that of other comparable small values (Wellman & Miller, 1986), suggesting there is something particularly difficult about the concept of zero for young children to grasp. Both historical and ontogenetic evidence have been used to promote the assumption that zero is special—distinct from other numbers. However, new research exploring nonsymbolic understandings of zero have begun to seriously undermine this perspective.

Recent studies with young children and nonhuman primates have suggested that both human and nonhuman primates may not treat the empty set (i.e., zero) as uniquely different from other numerical values. For example, after learning to select the smaller of two set sizes in order to receive a reward, both preschoolers (Merrit & Brannon, 2013) and rhesus monkeys (Merrit, Rugani, & Brannon, 2009) are more likely to select the empty set over larger set sizes in test, indicating that they appreciate that zero is the smaller value. These findings have been taken as evidence that primates understand the concept of zero and conceive of it as another value in the numerical continuum. Howard, Avarguès-Weber, Garcia, Greentree, and Dyer (2018) has taken this work further by exploring whether similar nonsymbolic concepts of zero may be present in some of our most distant relatives—honey bees.

Across three experiments, Howard et al. (2018) elegantly demonstrate that *even* insects order zero along the numerical continuum. In their first experiment, Howard et al. set out to determine whether honey bees spontaneously generalize an ordinal response rule to novel values, including the empty set. During training, bees were presented with pairs of displays containing two different numbers of shapes (any combination of two numbers between 1 and 4). In the "greater than" condition, a tasty sucrose reward was located on the platform corresponding to the display with the greater number of items and a bitter quinine solution (punishment) was located on the platform corresponding to the display with the smaller numerosity. That is, bees in the "greater than" condition were rewarded for approaching the more numerous array. Bees in the "less than" condition were trained on the converse relation; that is, they were rewarded with sucrose for approaching the display containing the smaller number. Once bees successfully learned the ordinal rule for their condition (performing above 80% accuracy), they were given test trials involving one of the trained values (1–4) and a novel set size, including 0. Remarkably, bees trained to select the smaller value selected the empty set more often than chance levels and bees trained to select the larger value selected the empty set less often than chance. Moreover, in both conditions,

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accuracy on these critical empty set test trials rivaled that of other trials in which they were presented with a novel set size of five, suggesting that the empty set was treated equivalently to any other novel numerical value. That is, zero did not appear to be "special".

In the second experiment, Howard et al. investigated whether bees would order the empty set when paired with another novel set size. In training, bees were again trained to select the smaller of two numerosities for set sizes ranging from 2 to five items. In test, the researchers presented the bees with displays containing zero and one items. Despite having no experience with either of these set sizes, bees more frequently landed on the platform corresponding to the empty set (zero items). They generalized the "less than" response rule to the two novel values, treating the empty set as a quantity less than one. In other test trials, the bees were presented with a zero versus two comparison. Notably, set sizes of two items had always been rewarded during training as it was the smallest value presented. In this case, the bees responded randomly on zero versus two trials, suggesting their responses were shaped by both the ordinal rule (leading to a preference for zero) *and* associative learning (leading to a preference for two).

In their final experiment, the authors provided a true test of whether bees treat the empty set as a value on the numerical continuum—that is, is zero just like any other number? A key signature of whether it is would be the presence of distance effects, such that accuracy with which two values are discriminated is dependent upon the numerical distance between the two values (Merritt et al., 2009). For example, we are more accurate when judging that 10 is less than 20 than when judging that 10 is less than 11—this is because 10 and 11 are more similar. Importantly, if bees treat zero as another number falling in their mental number line, then they should be less accurate on trials in which 0 is paired with 2 than when 0 is paired with 6. If, on the other hand, zero is special and distinct from other numbers, then the comparison would not be one of quantity but one of quality: akin to comparing apples to oranges. In that case, 0 should be considered no more similar to 2 than it is to 6, and as such their accuracy in distinguishing between these values should be comparable. To investigate this question, Howard et al. again trained bees to select the smaller of two values, for the values 0 through 6. When tested with novel shapes (but familiar set sizes), responses remarkably revealed the telltale distance effects: bees were more accurate when the empty set was paired with a large value (5 or 6) than when paired with a small value (1 or 2). Mirroring prior findings with rhesus monkeys (Merritt et al., 2009) and young children (Merritt & Brannon, 2013), honey-bee responses revealed that they treated zero as a quantity falling along the numerical continuum. That is, zero was just another number to them.

Given prior findings with monkeys and preschoolers, why is it so striking that honey bees demonstrate a similar capacity to represent zero? Well, given that honeybee brains are estimated to have one-thousandth the number of neurons as human brains, it suggests that this capacity is not dependent upon sophisticated neural architecture. More importantly, given how taxonomically distant bees are from primates, this tells us that the capacity to treat the empty set as a number has evolutionary significance. Either this ability traces back to a common ancestor—potentially as far back as 600 million years—or alternatively, these abilities have distinct evolutionary origins; regardless of its roots, either explanation points to the importance of this ability over evolutionary history.

Moreover, the work by Howard et al. provides a new perspective on developmental considerations. If even our furthest removed relatives treat zero as falling within the numerical continuum, then zero may not be so special. If that is the case, then why does understanding of symbolic zero pose such a challenge to young learners? One possibility is that having a concept of zero may be a necessary, but not sufficient, prerequisite for acquiring an understanding of the symbol "zero." Instead, symbolic representations may not readily align with this primitive concept of zero in the most obvious respect—it may not be clear to children how you can have something (i.e., "0") stand for nothing (i.e., the empty set).

By extending work on nonsymbolic representations of zero to an evolutionarily distant species, Howard et al. shed light on new avenues for future research. What are the neural requisites for having a concept of zero? How might we capitalize upon this primitive capacity to facilitate the learning of symbolic concepts? Why might this capacity have evolved? And of course, what other sophisticated mathematical capacities do we share with honey bees?

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