

# Semantic congruity affects numerical judgments similarly in monkeys and humans

Jessica F. Cantlon\* and Elizabeth M. Brannon\*

Department of Psychological and Brain Sciences and Center for Cognitive Neuroscience, Duke University, Box 90999, Durham, NC 27708-0999

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**Monkeys (*Macaca mulatta*) were trained to order visual arrays based on their number of elements and to conditionally choose the array with the larger or smaller number of elements dependent on a color cue. When the screen background was red, monkeys were reinforced for choosing the smaller numerical value first. When the screen background was blue, monkeys were reinforced for choosing the larger numerical value first. Monkeys showed a semantic congruity effect analogous to that reported for human comparison judgments. Specifically, decision time was systematically influenced by the semantic congruity between the cue (“choose smaller” or “choose larger”) and the magnitude of the choice stimuli (small or large numbers of dots). This finding demonstrates a semantic congruity effect in a nonlinguistic animal and provides strong evidence for an evolutionarily primitive magnitude-comparison algorithm common to humans and monkeys.**

nonhuman primates | numerical cognition | analog magnitude | distance effect

Humans and nonhuman animals discriminate numbers in a way that obeys the psychophysical tenets of Weber’s law (e.g., refs. 1–6; see ref. 7 for review). That is, animals and humans are faster and more accurate at comparing two numerical values as the ratio between them (min/max) decreases. For humans, the same pattern of ratio-dependent performance emerges regardless of whether the numerical values are presented as Arabic numerals, arrays of dots, or sequences of tones (e.g., refs. 1, 8–10). This response pattern is taken to indicate that humans and animals represent approximate numerical values as imprecise mental magnitudes (e.g., refs. 4 and 7). Thus, animals and humans are thought to represent approximate numerical values in fundamentally the same way. However, the specific process by which numbers are compared in monkeys and humans has not been specified. In this study, we investigate whether monkeys show a response signature of adult human comparison judgments: the semantic congruity effect.

When adult humans are asked “Which is smaller: an ant or a rat?”, they are much quicker to respond than when asked “Which is larger: an ant or a rat?” (e.g., refs. 11 and 12). In contrast, when adult humans are asked to compare two large animals, such as a cow and an elephant, they are much quicker to respond when asked “Which is larger?” than “Which is smaller?” This effect is known as the semantic congruity effect and has been reported for adult humans when they compare stimuli along a variety of continua, including the distance between two cities (13), line length (14), brightness (15), the intelligence of animals (16), adjectives of ordinal quality (e.g., good, fair, poor, or excellent; ref. 17), surface area (18), and Arabic numerals (19, 20). In all cases, the semantic relationship between the direction of the choice objective and the perceived magnitude of the to-be-compared entities affects the rapidity of human decision-making.

For numerical comparisons, the semantic congruity effect occurs in adults when the magnitude of the choice stimuli (small or large numbers) conflicts with the ordinal direction of the choice objective (“choose the smaller number” or “choose the larger number”). In a classic demonstration of the semantic

congruity effect on adult human numerical comparisons, Banks *et al.* (19) presented subjects with a pair of Arabic numerals ranging from 1 to 9. On some trials, subjects were instructed to choose the smaller number, whereas on other trials, they were instructed to choose the larger number. When the Arabic numerals were both small numbers (e.g., 2 and 3), subjects identified the smaller number faster than the larger number; when the Arabic numerals were both large numbers (e.g., 7 and 8), subjects identified the larger number faster than the smaller number. Thus, semantic congruity between the ordinal term in the verbal question (smaller or larger) and the subjective magnitude of the comparison numerals along the test continuum affects humans’ decision-making time.

Previous research has demonstrated that semantic congruity influences the decision-making process during the computation of the comparison rather than during stimulus encoding (12, 21). Shaki and Algom (12) presented adults with picture–word compounds consisting of animal pictures with the names of animals printed within the pictures. Subjects were asked to “choose the larger” or “choose the smaller” of the two animal pictures or two animal names. On congruent trials, the animal name matched the picture of the animal. However, on incongruent trials, the animal name and the animal picture did not match and were incongruent in size. For example, a picture of an elephant would have the word “cat” printed on it. A lack of congruence between the semantic content of picture–word stimuli produced Stroop-like interference when subjects either read the words or named the pictures of the compound stimuli (22).

Following the logic of Sternberg (23), the authors reasoned that if semantic congruity uses resources involved in the stages of stimulus encoding, Stroop and semantic congruity effects should interact in reaction time (RT). If, on the other hand, Stroop and semantic congruity effects occur at different stages of processing, their effects should be additive. The results indicated that trials in which the picture–word stimuli were incongruent produced increases in subjects’ RTs that were typical of the Stroop effect; however, these increases in RT were additive and did not interact with the semantic congruity effect. Stroop interference from the incongruent compound stimuli was attributed to the input stages of processing, whereas interference from the semantic congruity between the choice objective and the choice stimuli was attributed to the comparative stage of processing. Similar results have been obtained by Cech (21), who used perceptually degraded stimuli to show that impairments during stimulus encoding are additive with the effect of semantic congruity and do not interact. Again, the semantic congruity effect appeared to be a consequence of the comparison process rather than stimulus encoding.

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Abbreviation: RT, reaction time.

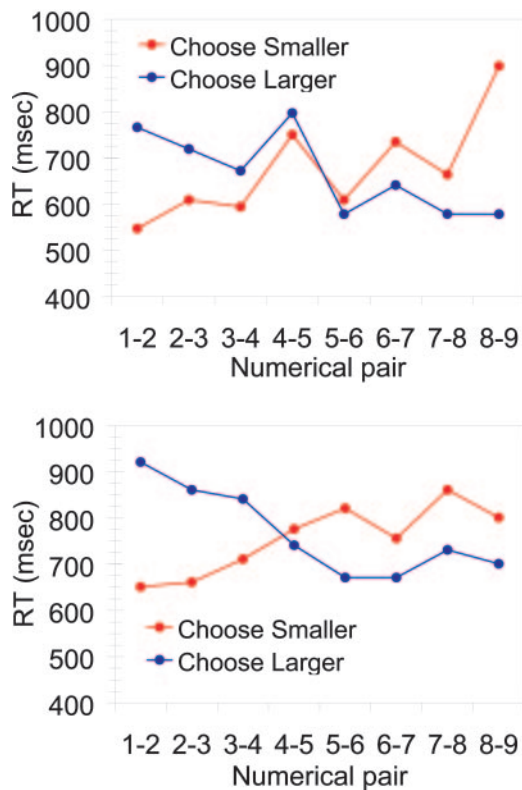
\*To whom correspondence may be addressed. E-mail: jfc2@duke.edu or brannon@duke.edu.

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**Fig. 4.** The semantic congruity effect. RT for Feinstein (*Upper*) and Mikulski (*Lower*) for each numerical pair at a constant distance of 1 during choose smaller and choose larger trials. The crossover pattern reflects the effect of semantic congruity on monkeys' numerical comparisons.

(Feinstein,  $r^2 = 0.84$ ,  $P < 0.05$ ; Mikulski,  $r^2 = 0.94$ ,  $P < 0.05$ ) and choose larger trials (Feinstein,  $r^2 = 0.84$ ,  $P < 0.05$ ; Mikulski,  $r^2 = 0.72$ ,  $P < 0.05$ ). Similarly, accuracy on numerical comparisons increased as numerical distance increased (Fig. 3*B*) for both the choose smaller (Feinstein,  $r^2 = 0.76$ ,  $P < 0.05$ ; Mikulski,  $r^2 = 0.88$ ,  $P < 0.05$ ) and choose larger (Feinstein,  $r^2 = 0.60$ ,  $P < 0.05$ ; Mikulski,  $r^2 = 0.63$ ,  $P < 0.05$ ) trials. This aspect of our data confirms the well established finding that monkeys represent number as analog magnitudes (1, 3–6).

The main finding was that both monkeys showed a semantic congruity effect (Fig. 4).<sup>†</sup> Monkeys were 186 msec faster on choose smaller trials than on choose larger trials when the two values were small (e.g., 1 vs. 2). In contrast, monkeys were, on average, 136 msec faster on choose larger trials than on choose smaller trials when the two values were large (e.g., 8 vs. 9). An ANOVA for Subject (Feinstein, Mikulski)  $\times$  Response Type ("choose smaller," choose larger)  $\times$  Numerical Magnitude [Small (1 vs. 2, 2 vs. 3, 3 vs. 4), Large (6 vs. 7, 7 vs. 8, 8 vs. 9)]<sup>‡</sup> on monkeys' RT to pairs of numerosities that differed by 1 revealed a main effect of Subject [ $F(1, 8) = 20.32$ ,  $P < 0.01$ ], reflecting overall faster RTs for Feinstein (mean, 667 msec) than Mikulski (mean, 764 msec) and an interaction between the Response Type and the Numerical Magnitude of the comparison stimuli [ $F(1, 8) = 38.55$ ,  $P < 0.001$ ]. The interaction reflects that, when the to-be-compared arrays were both small numbers, the

monkeys were faster to choose the smaller than to choose the larger of two arrays [ $t(5) = 5.60$ ,  $P < 0.01$ ], whereas when both arrays contained a large number of dots, monkeys were faster to choose the larger array than to choose the smaller of two arrays [ $t(5) = 3.61$ ,  $P < 0.05$ ].

The response patterns of monkeys on this task are remarkably similar to those reported for human subjects by Banks *et al.* (19) using Arabic numeral stimuli in a paradigm similar to ours. In light of these previous studies with humans, our data suggest that the cognitive process that monkeys use to compare the numerical value of two arrays of dots shares important features with the process used by humans for Arabic numeral comparisons.

### General Discussion

In summary, our results confirm that monkeys represent numerical values as analog magnitudes and demonstrate that semantic congruity affects the speed with which they compare numerical values. The qualitative similarity between the monkeys' response patterns and the response patterns of humans tested on analogous tasks with Arabic numerals (11, 19, 20) suggests that humans and monkeys are using the same mental-comparison algorithm for determining the larger or smaller of two numerical values.

Although language may have profound effects on some aspects of human thought (31), the fact that monkeys show a semantic congruity effect is evidence that certain computational processes have not been qualitatively altered by the emergence of language in humans. Although it is possible that the semantic congruity effect is a consequence of different psychological processes in monkeys and humans, this interpretation of the data seems less parsimonious than the notion that the effect results from a common, nonlinguistic comparative process in humans and monkeys. Thus, our study suggests that the computational process by which humans compare the relative magnitude of numerical values is evolutionarily conserved and language-independent.

Because monkeys do not represent numerical values as discrete quantities, the effect of semantic congruity on their response patterns cannot be explained by semantic conflicts that are hypothesized to result when humans mentally translate problems into linguistic symbols (e.g., ref. 19). There are several competing models of comparative processes that can account for the semantic congruity effect (see ref. 32 for review). Although our data cannot differentiate among these models beyond excluding those based on discrete representations, one model that could apply to both humans and nonhumans has been presented by Holyoak (20) and Petrusic (32). According to this hypothesis, the numerical values of a pair of stimuli are individually compared with reference values stored in memory to determine which of a given pair of values is the larger or which is the smaller (i.e., closest to the reference value). Reference values are context-dependent and are thought to represent the extreme values encountered in a given context. In our study, the extensive training on the values 1–9 may have prompted monkeys to use the value 1 as a reference point to determine which of two values was the smaller and 9 as a reference point to determine which of two values is the larger (33). Such an algorithm would produce the semantic congruity effect in response latency because the farther two values are from the reference point, the longer it takes to compare each of them to the reference point.

Regardless of which model best accounts for the semantic congruity effect, our demonstration of the effect in monkeys implicates the presence of a comparative process common to the comparison of Arabic numerals in humans and nonverbal numerical values in monkeys. Our data also indicate that the comparative process is not mediated by symbolic, linguistic, or otherwise uniquely human mechanisms. Instead, the semantic

<sup>†</sup>Examination of the choose larger function in Fig. 4 reveals that monkeys were faster at ordering large values, such as 8 vs. 9, compared with small values, such as 1 vs. 2. This pattern defies Weber's law and should be investigated further.

<sup>‡</sup>The 4-5 and 5-6 pairs were excluded because it was unclear whether they should be categorized as small or large.

congruity effect appears to be the signature of an evolutionarily primitive magnitude comparison mechanism.

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