

Numerical Matching to Sample in Rhesus Macaques (*Macaca mulatta*) and Humans

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INTRODUCTION

This experiment builds on previous numerical research with nonhuman primates. Our goal was to expand the range of numerosities on which rhesus macaques (*Macaca mulatta*) have been trained previously and to determine how a monkey represents those values. A central question is whether values are represented discretely or continuously, and whether data conform to Weber's Law (and the analog magnitude estimation mechanism it implies). We also compared accuracy and reaction time (RT) data from monkeys and human subjects to compare which quantification processes subjects used (subitization, estimation, or counting) and whether the quantification process was serial or parallel.

There are two aspects of this task that distinguish it from other studies of the numerical abilities of monkeys: the nonsimultaneity of sample and target presentation (which requires subjects to represent the sample) and the use of non-identical sample and target stimuli within the same modality. Additionally, the load on working memory was increased by the presence of distractors.

PROCEDURE

Subjects

The 5 monkeys currently working on this task were run daily in experimental chambers housed in isolated sound attenuated booths. Each booth contained a touch sensitive video monitor and an automatic pellet dispenser. Subjects were monitored via a closed-circuit video system. Each touch sensitive monitor was connected to an iMac G5 that presented all of the stimuli and recorded the accuracy and the RT data of each response. Correct answers were followed by a banana-flavored food pellet, a change in the color of the monitor, and a distinct sound. Incorrect answers were followed by a different distinct sound and a 4 second time out during which the screen is dark.

Each trial began with a start stimulus that the subject touched to indicate its readiness to begin the trial. The sample was shown in a random location on a blue background. Immediately after the subject touched the sample, the test screen displayed the target and distractors (currently 2) on a green background (Figure 1). Subjects had a limited amount of time to respond to the sample screen and to the target screens. If a subject did not respond during the allotted time, the same sound that followed incorrect responses was played, and subjects were given a 4 second time out.

Stimuli were generated by the computer prior to every trial. As shown in Figure 2, stimuli were composed of geometric figures that differed in size, shape, and color. The numerical values of the sample and distractors were chosen randomly. They were first trained on numerosities 1-4 to familiarize them with the task. During the next phase of training, the numerosities 1, 3, 5, 7, and 9 were presented, and finally all values 1-9 were used. Cues including shape, color, and identical sample and target configuration were progressively eliminated to ensure reliance on numerosity rather than secondary cues. For the two monkeys who have progressed the fastest, the size of the elements within each stimulus was randomized to control for surface area cues, and the density of the elements was also controlled. During subsequent phases of training, we will control for perimeter and test subjects with stimuli composed of heterogeneous shapes.

Human subjects

Experiment 1

Columbia undergraduates (n=24) worked in an isolated subject room and used a touch sensitive monitor. Subjects were not given explicit instructions to complete the task; instead, they began their session with 10 practice trials during which they were expected to discover the matching rule. After 10 practice trials, subjects could choose to practice again or move on to the 90 experimental trials. Correct responses were followed by a pink screen and distinct sound; incorrect responses were followed by a different sound and a one second time out. As with monkey subjects, accuracy and RT data were automatically recorded. Subjects were tested with the numerosities 1-9, with stimuli composed of black circles on white backgrounds. The elements in the sample and target were configured differently. The test screen consisted of the target and 3 distractors. After completing their session, subjects completed a questionnaire regarding their perception of the numerosities and their test taking strategy.

Experiment 2

In order to control RTs, a new group of Columbia undergraduates (n=19) completed the same task with a progressive time restriction. After completing practice trials, subjects completed 81 experimental trials in 3 blocks of 27 trials each. During the first block, subjects had 10.0 seconds to respond to the test screen. In the second and third blocks, subjects had 3.5 and 2.0 seconds to respond, respectively. Before each block began, a message appeared on the screen informing subjects of the time limit for the upcoming trials to encourage them to work quickly to complete all trials.

Figure 1: Procedure

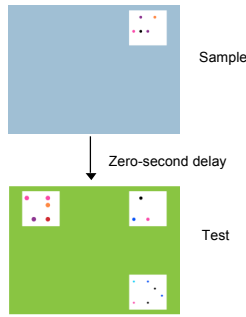
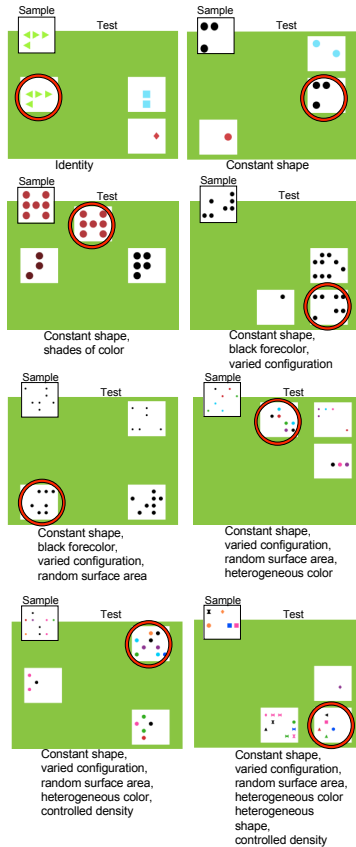


Figure 2: Sample stimuli



RESULTS

Monkeys

Data are presented from our two most advanced monkey subjects. Figure 3 shows the relative frequencies of correct responses and errors at each numerical value. Figure 4 shows the average accuracy as a function of the numerical distance between a distractor and the target. Figure 5 shows the median RTs for correct answers. These data show that the accuracy of responding to 1 was significantly higher than accuracy of responding to all other numbers, ($p < .001$), and that RT for 1 was shorter than the RTs to all of the other numerical values. These results suggest a highly accurate mechanism for discriminating 1, perhaps like human subitization. Additionally, there appears to be an anchoring effect due to the recognition paradigm; because 1 and 9 were the smallest and largest numerical values, errors (when 1 or 9 is the sample) occur only above or below the sample. Because the distractor values to 1 and 9 are limited, the numerical distance between the sample and average distractor is increased. This results in higher accuracy and faster RT to 1 and 9 compared to those of adjacent values.

Human Subjects

Median RTs for correct answers for human subjects in Experiment 1 (n=24) are shown below (Figure 5). In the follow-up questionnaire, many participants reported subitizing, chunking, and counting for most values, but often not arriving at an absolute value for 9. This is mirrored in the anchoring effect of lower RT for 9. No participant reported relying solely on estimation. Of those participants who reported a dichotomous memory strategy, they reported a visual representation of smaller numbers (usually 5 and below) and a verbal representation of larger numbers. Results for Experiment 2, in which response time was limited, are shown in Figures 6 and 7. Mean response values and standard deviations, as well as the coefficient of variation, are shown in Figures 8 and 9 for monkey subjects (n=2) and human subjects in Experiment 2 (n=19).

Figure 3: Response probabilities for monkey subjects (n=2)

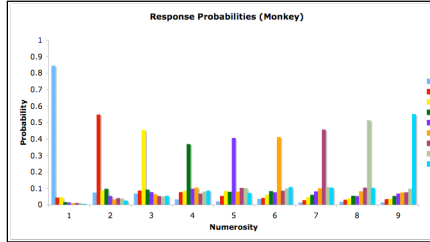


Figure 4: Average accuracy by nearest distractor distance for monkey subjects (n=2)

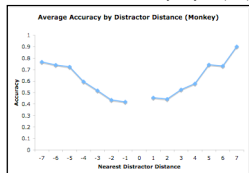


Figure 5: Median correct RTs for monkey subjects (n=2) and human (n=24) subjects

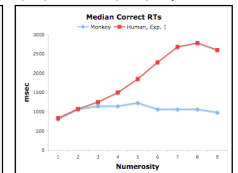


Figure 6: Accuracy for each time condition in human experiment 2 (n=19)

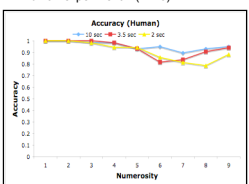


Figure 7: Median correct RTs for each time condition in human experiment 2

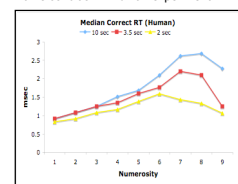


Figure 8: Mean response and standard deviation for monkey (n=2) and human (n=19) subjects

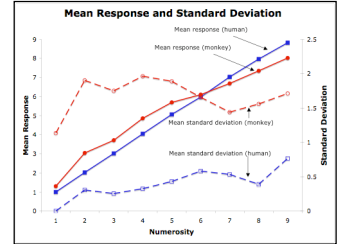
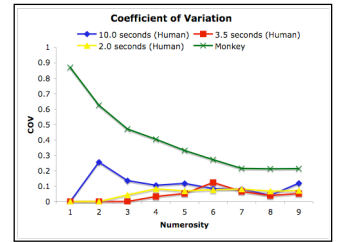


Figure 9: Coefficient of variation for monkey (n=2) and human (n=19) subjects



CONCLUSIONS

The strongest similarities between the performance of monkeys and human subjects was seen in their accuracy and RT to 1 and in the anchoring effect.

In general, RTs for monkeys are much shorter and have a much smaller range than those of human subjects. Such results are consistent with a reliance on numerical estimation in monkeys and the use of a parallel quantification mechanism. Exact, serial enumeration would result in a smooth ascending slope like that obtained from human subjects in Experiment 1.

Experiment 2 shows that even when required to respond as quickly as monkey subjects, the accuracy of human subjects on numerosities 1-3 was nearly perfect. This result suggests that they subitized these values. Lower accuracy in monkeys for these same numerosities suggests that they used a different strategy to perform this task.

Accuracy for monkey subjects shows a distance effect because average accuracy increases with increasing distance of the nearest distractor. It is possible, however, for results to show a distance effect without conforming to Weber's Law. This is true in the present studies because the standard deviation for responses does not increase monotonically and the coefficient of variation is not constant.

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