

## IMPACT OF PATH PARAMETERS ON MAZE SOLUTION TIME

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### INTRODUCTION

When a subject is stationary, eye movements and attention are commonly employed jointly to search the visual environment, gather information about objects in it, and guide action (1). When eye movements are not allowed, attentional mechanisms become the main, if not the only, means for analyzing the environment. Spatial attention has been studied in psychophysical experiments within several contexts, including stimulus detection (5) and discrimination (3, 8), curve tracing (4), and searching complex displays (6). A specific case involving spatially modulated attention is solving mazes. In this case, the subject is presented a visual maze and has to decide whether a given path in the maze exits or not. If the maze is complicated, eye movements play a prominent role in its solution (2); on the other hand, relatively simple mazes could be solved without eye movements, i.e. with eyes fixed. In that case, a basic question relates to the minimum viewing time needed to solve the maze successfully. This minimum viewing time would provide an estimate of the rate at which the presumed attentional process operates. Then, given adequate viewing time, it would be important to identify those maze elements the analysis of which consumes the time taken to respond correctly as to whether the maze exits or not. Finally, a different question concerns testing the cross-species assumption, namely identifying the similarities and differences in the ways that different human subjects and subhuman primates solve mazes. Here we report on the results of experiments which addressed these different issues.

### METHODS

#### *Maze Stimuli.*

Maze stimuli (Fig. 1) were randomly generated. Each was bounded by an octagonal perimeter and contained a square start 'box' at their center. The area within the maze was uniformly filled with a single main path (connected to the start box), distractor paths, and path fragments. The main path followed a 'random walk' from the start box through the maze, changing direction with a probability of 0.2 at each step. Each distractor path was connected to an exit in the maze perimeter. Path fragments began and ended entirely within the maze. Mazes were masked in the human experiments by replacing all the line segments in the grid in a single screen refresh, to obliterate the spatial structure of the paths (Fig. 1, right). 'Exit' mazes refer to those in which the main path was connected to an exit at the maze perimeter (Fig. 1, left), and 'no-exit' mazes those in which

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Fig. 1. - *Maze stimuli.*

A. Examples of maze stimuli including an exit maze with 3 turns in the main path (left), a no-exit maze with 1 turn (middle), and the masking grid (right) presented at the end of the maze display interval.

the main path reached a blind ending within the maze (Fig. 1, middle). An extra distractor path was added to no-exit mazes to keep the total number of exits constant at 3 for both exit and no-exit mazes (so that the task could not be performed by counting exits).

Human subjects solved the same set of 700 different mazes randomly constructed from an underlying 13 by 13 element square grid (minus the corners to produce the octagon). This set of mazes was balanced for exit status (350 exit and no-exit mazes), and the number of turns in the main path (from 0 to 6 turns, 100 different mazes of each turn number). The monkey solved mazes that were slightly less complex, and were constructed on a square grid of 11 maze elements. Both humans and the monkey solved an additional set of mazes constructed from a 23 element grid in which the main path was always straight. Half of these mazes were rotated 45° counter-clockwise, so that across the set the main path could travel in one of eight radial directions relative to the central start box. The length of no-exit paths in this case varied randomly from 3 to 9 grid elements, while main paths that reached an exit were always 10 elements long. Mazes for humans (presented on a video monitor) and the monkey (back projected by a LCD projector on a tangent screen) subtended 30 degrees of visual angle edge to edge.

#### *Task.*

Trials began with the appearance of a spot stimulus at the center of display serving as a fixation target for both humans and the monkey. Humans were instructed to maintain fixation of this target throughout the trial. Human subjects performed the task in the absence of observable saccades (occurring in less than 3% of trials). Fixation performance was monitored and recorded using a video camera positioned close to the eye. The monkey was prepared for the recording of eye position via a scleral search coil (Judge et al. 1980) using standard aseptic surgical techniques. Care and treatment of the animal during the experiments conformed to NIH Principles of Laboratory Animal Care (revised 1995). All experimental protocols were approved by the appropriate institutional review boards. The monkey was required to maintain fixation of the central target within a 1.5° window. After a variable period of fixation, a maze stimulus appeared with the start box centered on the fixation target. Human subjects were instructed to depress either the numeral 1 if the maze were an exit maze, or the numeral 2 if the maze were a no-exit maze, on the numeric keypad of a computer keyboard. The monkey indicated its response by depressing one of two foot pedals, the left pedal in the case of exit mazes, and the right pedal in the case of no-exit mazes. If the monkey's response was correct, it received a drop of liquid reward through a juice delivery tube positioned close to its mouth.

## RESULTS

We used octagonal mazes with a 'main' path that started at the center of the maze and exited the maze or not, in different trials (Fig. 1); the response required was to indicate whether the path exited or not. The rest of the maze was filled with distractor paths, and the main path varied in length and in the number of turns it contained. In the first experiment, involving only human subjects, we sought to determine the effect of viewing time on solving the maze correctly. For that purpose, we presented the maze for different periods of time, followed by a masking grid stimulus. The probability of correct maze solution increased with viewing time in a negatively accelerating fashion and reached a plateau at  $p = \sim 0.85$  from 500 ms onward (Fig. 2a).

Next we assessed the affect of maze parameters on the reaction time (RT), for correct responses in both human subjects and monkeys, when they were given adequate viewing time. We found that the RT in both species increased as a linear function of the number of turns and the main path length (Fig. 2b). The slopes were similar between the two species with respect to the number of turns but differed appreciably with respect to path length in that the slope for humans was 2.5 times greater than that for the monkey; thus path length information was processed much faster by the monkey.

## DISCUSSION

Here we have shown that human and monkey subjects can solve mazes in a similar fashion relying on a time-consuming spatial analysis of maze elements, namely path length and number of turns. In a previous study, in which we analyzed scanning eye movements of human subjects solving complex rectangular mazes (2), we found that the time taken at each point of fixation exhibited a linear dependence on the length and number of turns of the section of the path between the current and the next fixation point. In the present study the eyes were fixated, and a similar dependence was found. Therefore, it seems that the same basic mechanism underlies maze solution in both cases, with the difference that, if the maze is fairly complex, the postulated attentional analysis would be applied multiply along the maze path to guide eye movements. Our findings are in keeping with regarding spatial attention as a mobile zone of enhanced visual processing that can be covertly re-positioned in a visual scene in the absence of saccadic eye movements. In that respect, spatial attention has been studied in various contexts, including, for example, stimulus detection (3), stimulus discrimination (8, 4), and curve tracing (6). Finally, with respect to the hypothesized process of mentally traversing the maze path, this can be regarded as an application of a "visual routine" (7) by which relative spatial arrangements are analyzed.



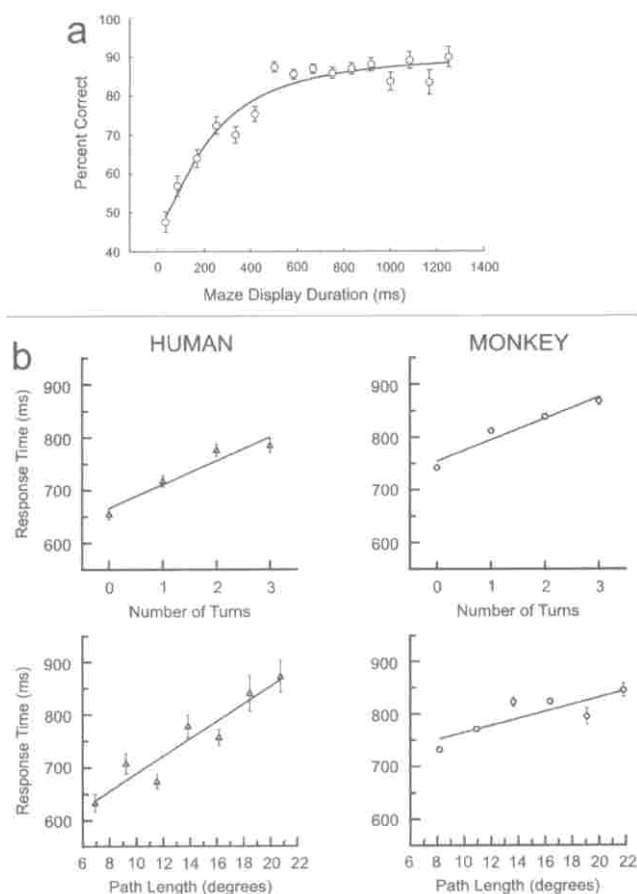


Fig. 2. - Psychometric function and relationship between response time and spatial parameters of the main maze path.

a. Mean percent correct performance across the 10 human subjects as a function of maze display duration. Display duration was a randomly selected from a list of integer multiples of 16.67 ms screen frames (at 60 Hz refresh rate). The briefest display duration was 33 ms (2 video frames), followed by a series of durations ranging from 5 (83.3 ms) to 75 video frames (1250 ms) in 5 frame (83.3 ms) increments. Mazes were displayed for these durations unless the subjects responded before the selected duration had elapsed, in which case the maze stimulus was extinguished and the trial terminated, introducing scatter into actual maze display time. Maze display times were subsequently binned (using the above intended values as the upper limits of each bin). A least-squares iterative logistic regression was applied to the mean correct performance of the 10 human subjects within each display duration bin (implemented in the graphing program Axum) to produce the illustrated fit. Performance accuracy increases monotonically from 33 to 500 ms, after which little increase in accuracy is evident. b. Mean response times ( $\pm 1$  s.e.m.) were adjusted for the effect of maze exit status. These adjusted means were obtained from an analysis of covariance (BMDP statistical package) in which response time was the dependent variable, turns or length were factors, and exit status was treated as a covariate. Human performance is illustrated on the left, the performance of the monkey on the right. For both species, response time (RT) exhibited a linear dependence on the number of turns (middle;  $RT_{\text{human}} = 665.9 + 45.0 T$ ,  $p < 0.05$ ,  $R^2 = 0.89$ ;  $RT_{\text{monkey}} = 754.6 + 40.5 T$ ,  $p < 0.05$ ,  $R^2 = 0.91$ ;) and the length (bottom;  $RT_{\text{human}} = 522.8 + 16.5 L$ ,  $p < 0.01$ ,  $R^2 = 0.90$ ;  $RT_{\text{monkey}} = 698.2 + 6.7 L$ ,  $p < 0.05$ ,  $R^2 = 0.68$ ) of the main path in the maze. This analysis was restricted to trials in which the grid was not shown (in the case of human subjects), and mazes with 3 or fewer turns, and a path length of 9 or fewer maze squares (8 or fewer squares in the case of the monkey).

## SUMMARY

In order to compare spatial attention and visual processing capabilities of humans and rhesus macaques, we developed a visual maze task both could perform. Maze stimuli were constructed of orthogonal line segments displayed on a monitor. Each was octagonal in outline and contained a central square (the 'start box'). A single ('main') path, containing a random number of turns, extended outward from the start box, and either reached an exit in the maze's perimeter, or a blind ending within the maze. Subjects maintained ocular fixation within the start box, and indicated their judgment whether the path reached an exit or not by depressing one of two keys (humans) or foot pedals (monkeys).

Successful maze solution by human subjects required a minimum viewing time. Replacing the maze with a masking stimulus after a variable interval revealed that the percent correct performance increased systematically with greater viewing time, reaching a plateau of approximately 85% correct if mazes were visible for 500 ms or more. A multiple linear regression analysis determined that the response time of both species depended upon several parameters of the main path, including the number of turns, total length, and exit status. Human and nonhuman primates required comparable time to process each turn in the path, whereas monkeys were faster than humans in processing each unit of path length. The data suggest that a covert analysis of the maze proceeds from the center outward along the main path in the absence of saccadic eye movements, and that both monkeys and humans undertake such an analysis during the solution of visual mazes.

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