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Cognitive spatial-motor processes

6. Visuomotor memory scanning

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Summary. Fourteen human subjects performed in a modified Sternberg memory-scanning task. First, they made a series of 2–6 movements in different directions from a central point towards peripheral lights on a planar working surface ("list trials"). Then, after a warning signal, one of the previous list stimuli, except the last, was presented again ("test trial"). Subjects were instructed to move in the direction of the stimulus which was presented next in sequence in the list. The mean reaction time (RT) in the test trials increased as a linear function of the number of movements, *S*, in the list: Mean RT (ms) $= 105 + 205.8S$ ($2 \leq S \leq 6$). This finding suggests that the task involves memory scanning of visuomotor list items.

Key words: Memory scanning – Movement – Movement direction – Reaction time – Human

Introduction

An important aspect of cognitive function relates to memory operations. A particular kind of such an operation is retrieval of memorized items in a list. Sternberg (1966, 1969) discovered that this operation involves memory scanning. He devised a series of tasks that involve recognition of items in a memorized list. Typically, the stimulus ensemble consists of a list of items. A subset of this list is presented sequentially to a subject, followed by a test stimulus from the stimulus ensemble. Three variants of these tasks were used, each of which required a different response by the subject involving item recognition, context-recall, or context-recognition. It is noteworthy that memory scanning has been described in rhesus monkeys (Sands and Wright 1982). In the *item recognition* task (scanning-to-recognize) the subject is required to make one response ("positive response") if the test stimulus was contained in the list presented (the "positive set"), and a different response ("negative response") if the test stimulus was not contained in the positve set. It was found that the RT, from the presentation of the test stimulus to the response, was a linear function of the number of elements in the positive set with a slope of 38 ms/stimulus item (Sternberg 1966, 1969). This finding was interpreted as evidence for a process of memory scanning: the list of items in the positive set is scanned and the test item is compared to each item in the list. The higher the number of items in the list, the more time the process takes, with an average 38 ms item-comparison time. Other findings suggested that this memory scanning is exhaustive (i.e. all items in the list are compared) rather than self-terminating (i.e. stop when a positive comparison is found). The increase in the RT with the length of the list is robust and is observed even for well learned lists. Although other hypotheses have been advanced, memory scanning has held its ground adequately (Sternberg 1975).

The *context-recall* task requires location of an item in the list ("scanning-to-locate") rather than recognition. A list of items is shown sequentially to a subject followed by a test stimulus selected randomly from the items presented, except the last. The subject is required to identify (e.g. by name) the item that followed the test item in the list. Under these conditions, the RT again increased with the number of items in the memorized list, but the process was self-terminating as evidenced by the increase of the RT with the serial position of the item in the list and the linear increase of RT with both the number of items in the list and their serial position. The slope was 124 ms/item. Assuming that, on the average, one-half of the items on the list were scanned (given a self-terminating process) the slope is effectively approximately 250 ms/item, indicating that "scanning-to-locate" is about 6–7 times slower than "scanning-to-recognize".

Finally, the *context-recognition* task involves recognition of contextual information, that is information concerning serial order of items in the list. Again, a list of items is presented sequentially to a subject but a pair of items in that sequence is presented as the test stimulus. The subject

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was required to decide whether the left-to-right order of the pair was the same as its temporal order in the list. The RT increased as a linear function of the number of items in the list, and the slope was the same as in the context-recall experiment described above. However, the Y-intercept was about 100 ms higher in the present case, reflecting the additional time taken to decide the serial order of the items presented.

In summary, the "memory scanning" tasks of Sternberg provide a powerful tool by which cognitive operations on memorized lists can be investigated. In the present experiments, we adapted the *context-recall* task for a study of memory-scanning in the motor system in the absence of verbalization. The memorized items were visually guided movements made in two-dimensional (2-D) space and in the direction of lights turned on sequentially on a planar working surface, and the test stimulus was one of the lights in the previous sequence, except the last: the subject was required to move in the direction that followed, in the sequence, the direction of the test light. We wanted to define the human capacities in performing the task. Preliminary results were presented (Georgopoulos et al. 1989c).

Methods

Subjects

Fourteen unpracticed human subjects (7 females and 7 males) participated in these experiments. They were all healthy volunteers recruited from the academic environment of the Johns Hopkins University School of Medicine. All subjects were right-handed and performed with the right hand.

Experimental apparatus and task

A two-dimensional planar working surface and an articulated manipulandum were used. The working surface was a frosted plexiglass square screen, tilted 15 degrees from the horizontal towards the subject. The manipulandum was described previously (Georgopoulos et al. 1981). A 10 mm diameter transparent plexiglass circle was attached to the distal end of the manipulandum which the subjects grapsed with the hand pronated. Motion of the manipulandum over the working surface was free and almost frictionless. A He-Ne laser beam was back-projected through a system of mirrors onto the working surface, on which it appeared as a small red dot of light. The beam could be turned on or off, and the spot moved to different positions on the plane using two microprocessor controlled galvanometers.

The *task* was entirely non-verbal, unlike Sternberg's task (1969). A *behavioral unit* (Fig. 1) consisted, successively, of (a) a set of trials in a list (list length = 2–6 directions), (b) a time period of 0.5 s following the last trial in the list, (c) a warning signal (buzz), (d) a time period of 1 s, (e) a single test trial, and (f) a time period (3 s) followed by another behavioral unit. During a *trial in the list* a light appeared in the center of the plane, and the subject was required to move the manipulandum from the center and capture the light within the transparent plexiglass circle of the manipulandum and keep it captured within a 10 mm positional window ("center window"); exit from this window before the onset of a peripheral light (see below) restarted the trial with the light at the center ("center hold error"). After a period of time of 0.2 s the light was turned off at the center, and was then turned on at another position on an imaginary circle of 2 cm radius. The subject was required to move the manipulandum in the direction of the stimulus; the trial ended when an imaginary circle of 3 cm was crossed (the "outer window"). This ensured a minimum movement amplitude. The direction of the vector from the center to the stimulus was the "stimulus direction". After an intertrial interval (0.3 s) during which the beam was off, the trial was repeated with a different stimulus direction. Two to six stimulus directions were used in a particular behavioral unit. They were chosen randomly without replacement from a set of 8 directions equally spaced within the 360° directional continuum; the origin in the circle of the directions in a set of list trials was random. The last list trial was followed by a time period of 0.5 s, a buzz of 0.5 s duration, and another time period of 1 s; during these times the beam was turned off. Then the light appeared at the center signaling the beginning of the *test trial.* The subject captured that light with the manipulandum, as above, and, after a period of 0.2 s, the light was turned off at the center and turned on in one of the positions of the list trials except the last. The subject was required *to move the manipulandum in the direction that followed that of the test stimulus in the previous list sequence.* The subjects were instructed to move as fast and as accurately as possible in the appropriate direction; however, the emphasis was on accuracy. "Correct responses" were considered to be those movements during which the manipulandum stayed within a sector of $\pm 22°$ of the correct direction from the moment of exiting the center window until the moment of exiting the outer window; all other movements that did not stay within that sector were considered "directional errors". The movement directions ("directional responses") at the moment of exiting the outer window were retained for both correct responses and directional errors for further analysis.

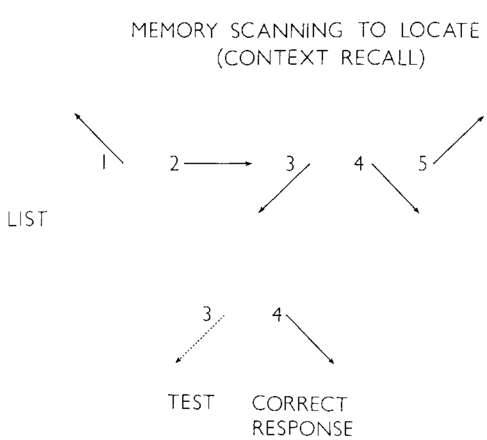

Fig. 1. Task (see text for details)

Behavioral units with various list lengths were presented in a randomized block design. Within a block of a particular list length, five repetitions of all possible serial positions of stimulus directions in the list were presented in a completely randomized design. Behavioral units with directional errors were repeated with the same list length but different, randomly selected, list directions.

Data collection

The experiment was controlled using a PDP11/34 laboratory minicomputer. The X-Y position of the center of the plexiglass circle at the distal end of the manipulandum was measured with a precision of 0.125 mm as described previously (Georgopoulos et al. 1981). This position was sampled every 10 ms and the data stored on-line in digital form.

Data analysis

The *direction of the movement* was determined every 10 ms. If the movement direction stayed within the angular window mentioned until the outer window was crossed, a click indicated to the subject that that was a correct response. The *directional spread* of movements made within a particular condition (e.g. list length, serial position, etc.) was estimated by calculating the circular standard deviation (CSD) (s_0 in Mardia 1972):

$$\text{CSD (in degrees)} = (-2 \ln \bar{R})^{1/2} \times 180/\pi \qquad (1)$$

where $\ln \bar{R}$ is the natural logarithm of the mean resultant. For this calculation all movements (correct responses and directional errors) were used. The *RT* was from the time the light appeared in the peripheral location until the manipulandum crossed the inner (center) window. The results were analyzed using standard statistical techniques (Snedecor and Cochran 1980).

Results

Behavioral performance

The performance in the task was affected by the list length and the serial position of the test direction in the list. In general, the error rate increased with increasing list length but decreased for test directions with higher serial positions in the list, that is for directions that came later in the list and were, therefore, more recent at the time of presentation of the test stimulus. Two measures were used to assess performance in this domain, namely the CSD and the percent directional errors, as defined in *Methods*. The former quantifies the directional variability of the movements (correct responses and directional errors considered together), whereas the latter is the percent of movements which did not satisfy the stringent criterion for a correct response. In Fig. 2 the average CSD (across subjects) is plotted against the serial position of the test direction in the list for each of the 5 list lengths used (list length = 2 to 6, numbers in parentheses). It can be seen (a) that the CSD increased with longer list lengths, as evidenced by the higher curves, and (b) that the CSD tended to decrease with serial position, especially when the test direction was the last one presented in the list (i.e. highest serial position) and therefore was the most recent at the time of presentation of the test stimulus. Figure 3 shows the dependence of CSD on list length, S, for serial position 1 for

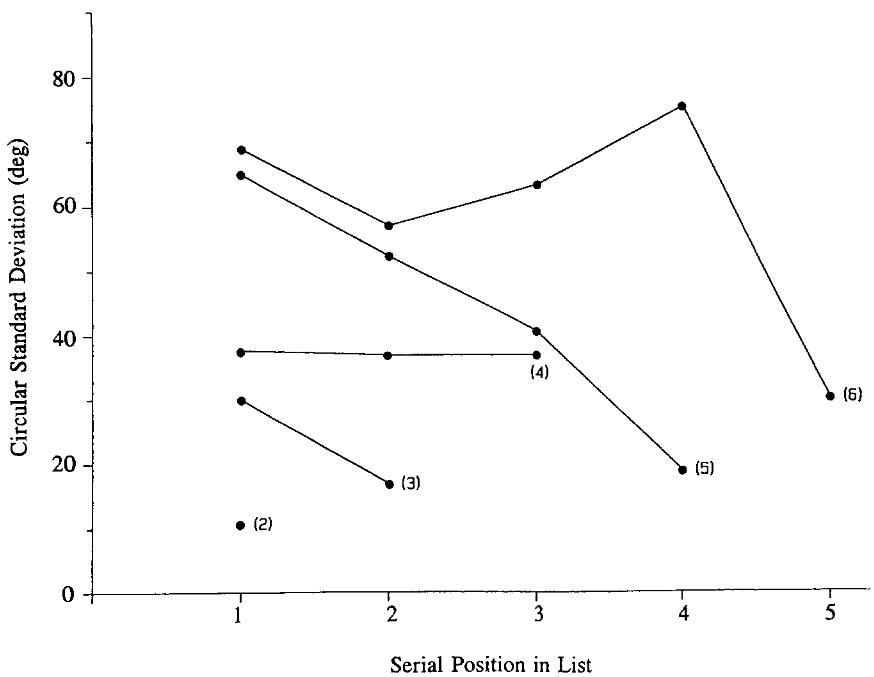

Fig. 2. Mean (across subjects) CSD is plotted against serial position of test direction in list for different list lengths (numbers in parentheses)

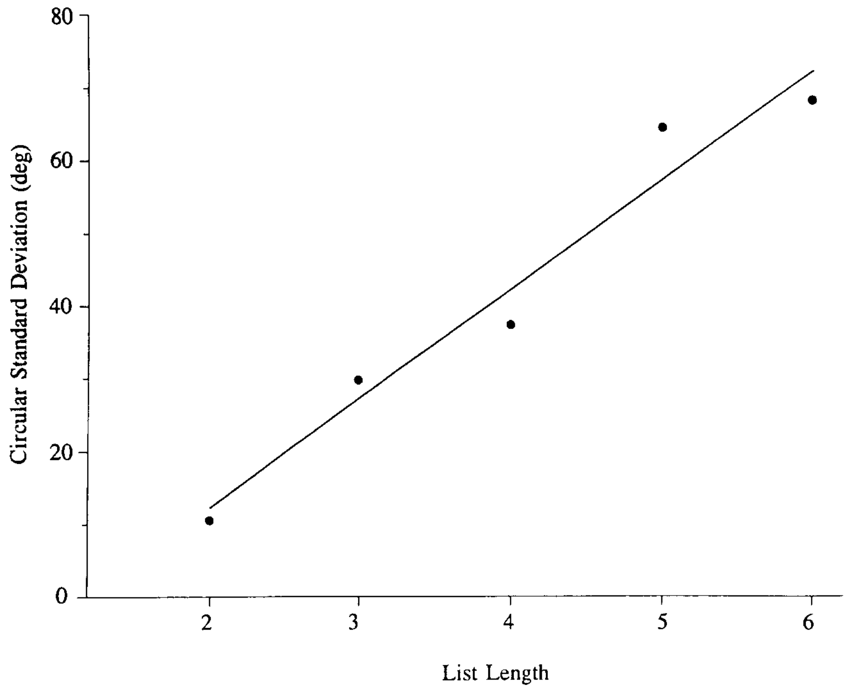

Fig. 3. Mean CSD is plotted against list length for serial position 1

which the data were unaffected by the "recency effect" mentioned above. The regression equation was:

$$\text{Mean CSD (for serial position 1)} = -17.9 + 15.1S \quad (r^2 = 0.958). \quad (2)$$

Similar coefficients were obtained for serial position 2. The increased directional variability described above was spread on either side of the correct response, and there was no systematic trend for the mean movement direction with respect to the correct response.

Finally, the relations between percent directional errors (see *Methods*) and list length and serial position resembled those depicted in Fig. 2 for CSD. This was to be expected for both measures are estimates of directional spread. The regression equation for mean percent directional errors vs. list length for serial position 1 was:

$$\text{Mean Percent Directional Errors (for serial position 1)} = 9.8 + 10.9S \quad (r^2 = 0.962). \quad (3)$$

Reaction time

The mean RT of list trials preceding each correct response to the test stimulus was calculated. This value provides the background RT, that is for those trials that did not involve a memory retrieval process. The grand mean RT of list trials preceding correct responses was 418 ms $\pm$ 66.5 (mean $\pm$ SD, N = 555 correct responses). Since center hold errors (see *Methods*) could occur in the list trials, it is interesting to know the time that elapsed between the onset of successive list stimuli to which correct responses were made; the overall mean ($\pm$ SD) was 1.49 $\pm$ 0.91 s (N = 555 correct responses).

In Fig. 4 the mean (across subjects) RT is plotted against serial position for different list lengths (numbers in parentheses). It can be seen that the RT increased with list length, as evidenced by the higher curves of list lengths, but it also tended to decrease with higher serial positions, that is when the test direction happened to be presented later in the list and therefore was most recent when the test stimulus was presented. However, this effect did not attain statistical significance in the multiple regression analysis, in which only the list length had a significant effect on the RT ($p < 0.001$, F-test); the list length x serial position interaction term was not statistically significant ($p > 0.05$, F-test).

The dependence of mean RT on list length was first analyzed within serial position 1, that is for data unaffected by the "recency effect" described above. It was found that the mean RT was an increasing linear function of list length, S, according to the regression equation.

$$\text{Mean RT (ms) for correct responses (for serial position 1)} = 92.1 + 208.9S \quad (r^2 = 0.994). \quad (4)$$

Since the serial position effect was not, overall, statistically significant (see above), a regression analysis was performed for all data averaged across serial positions. The equation obtained was (Fig. 5).

$$\text{Mean RT (ms) for all correct responses} = 105 + 205.8S \quad (r^2 = 0.999). \quad (5)$$

An increase of RT with list length was observed consistently in individual subjects. The slopes and r^2

obtained for individual subjects and all data (as in Eq. 5) are given in Table 1.

The RT of directional errors (see *Methods*) also increased with list length. The regression coefficients were similar to those in Eq. (5) above.

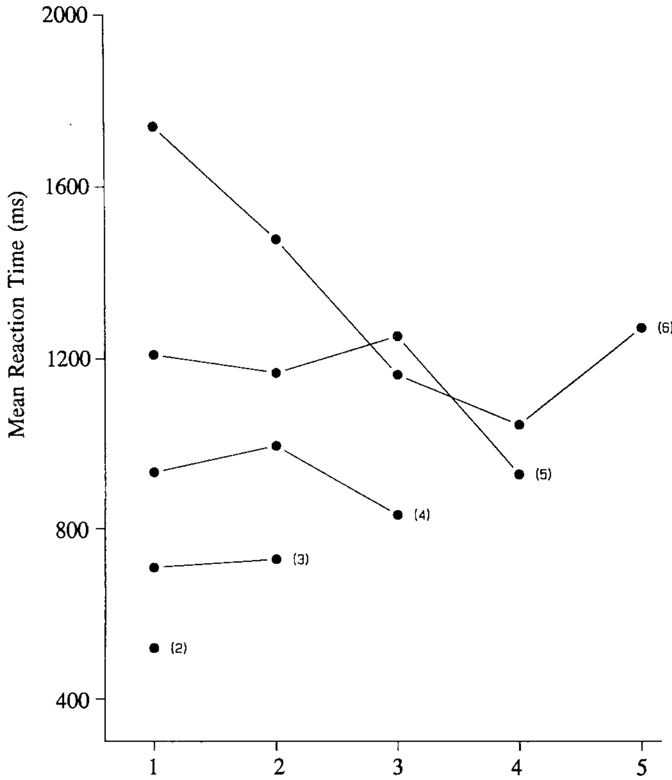

Fig. 4. Mean RT of correct responses is plotted against serial position of test direction in list for different list lengths (number in parentheses)

$$\text{Mean RT (ms) for all directional errors} = 78.9 + 215.7S \quad (r^2 = 0.998). \tag{6}$$

A statistical comparison showed that the slopes and elevations in Equations 5 and 6 above did not differ significantly (F-tests, $p > 0.05$). Therefore, the data for correct responses and directional errors were combined and the resulting regression equation was.

$$\text{Mean RT (ms) for all data combined} = 86.0 + 211.4S \quad (r^2 = 0.999). \tag{7}$$

Discussion

The major goal of the present experiments was to define the capacities of human subjects to scan in memory arm

Table 1. Slopes of the regression line (mean RT versus list length, correct responses) for individual subjects

Subject number	Subject ID	List length	Slope	r^2
1	S10	4	247	0.999
2	S11	6	301	0.960
3	S12	4	110	0.973
4	S13	4	338	0.997
5	S14	4	111	0.984
6	S15	5	173	0.943
7	S16	5	219	0.792
8	S17	5	157	0.761
9	S18	4	259	0.998
10	S19	4	98	0.985
11	S20	4	297	0.987
12	S21	4	167	0.917
13	S22	6	121	0.808
14	S23	6	149	0.998

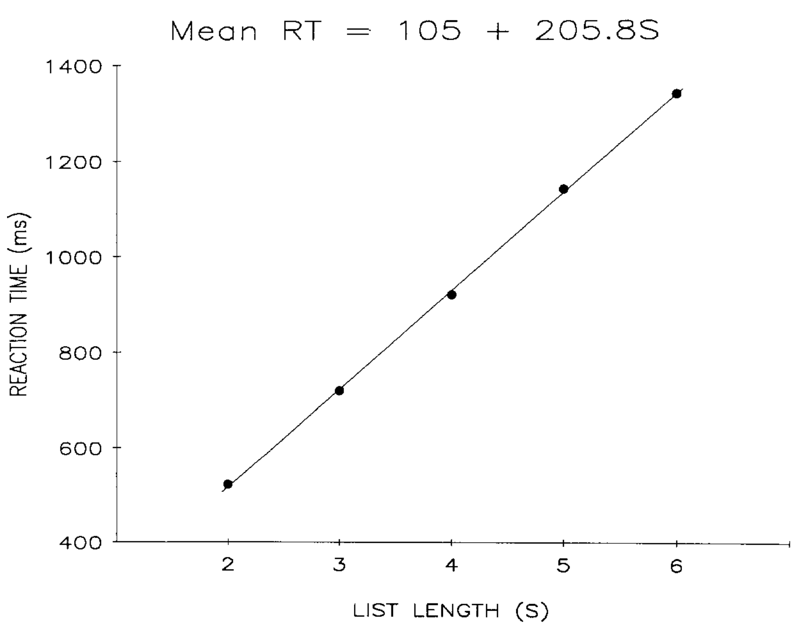

Fig. 5. Mean RT of correct responses is plotted against list length

movements aimed at visual targets. We focused on the direction of 2-D arm movements, in continuation of our previous behavioral (Georgopoulos et al. 1981; Georgopoulos and Massey 1987, 1988) and neurophysiological studies (Georgopoulos et al. 1982, 1983, 1989a, b). Our ultimate goal is to train monkeys to perform the same task and then record the activity of single cells in their brain during performance, in an effort to elucidate the neural mechanisms underlying cognitive spatial-motor processes (Georgopoulos and Massey 1987; Georgopoulos et al. 1989a).

The task used in the present experiments required the subjects to make a movement in a direction determined by a series of movement directions ("list directions") immediately preceding the test stimulus. The direction required was the one that followed the direction of the test stimulus when the latter appeared in the series. Successful performance in the task required (a) at least some recall of the list, and (b) generation of a movement direction that depended on the serial position (i.e., context) of the test stimulus in the list. Thus the task closely resembled that used by Sternberg (1969) in the context-recall experiments which involved recall of sequentially presented visual items (see *Introduction*). The main difference between the present experiments and those of Sternberg was that our experiments required a visuomotor response during the list trials, that is the production of movements in the direction of visual stimuli, whereas in Sternberg's case no action was required during the presentation of list items.

A salient finding of this study was the strong and linear dependence of the mean RT on the number of items in the list. This effect was present in all subjects and was the only statistically significant effect on the RT. The linear increase of RT with list length suggests a memory scanning of list items (Sternberg 1969). It is interesting that this effect was observed also for directional errors. This suggests that subjects scanned in memory list items even if the response direction was quite variable.

The slope of RT of correct responses vs. list length in the present experiments was 205.8 ms/item. This is much higher than that observed by Sternberg (1969) which was 124 ms/item. Several factors probably contributed to the higher slope observed in the present experiments. First, the list items in the present experiments were reaction-time movements that were probably more disruptive of memory processes than the passively displayed items presented by Sternberg because a response (i.e. a movement) was required in each trial in the list. Second, the items to be memorized were complex for they comprised stimulus-response elements rather than stimuli alone. Moreover, they could be memorized in different ways which could create a choice situation for the performing subject. For example, one could memorize the location of the list stimulus and the movement towards it or the movement direction alone; also, one could memorize the sequence in a symbolic form (for example, using numbers, 1, 2, 3, 4,. . .) and associate with a number the position of the light and/or the movement direction. Finally, the time between successive list stimuli was precisely controlled by Sternberg (1969) at 1.2 s per digit, whereas in the present study this time was longer (1.49 s on the average) and variable (SD of 0.91 s) due the variability in behavioral times (RT, movement time) and performance (e.g. center hold errors).

In summary, the coding and memorizing of stimulus-response items in the list, the potentially disrupting effect of reaction-time movements within the list, and longer average interstimulus intervals in the list could all have contributed, among other possible factors, to the higher slope of scanning-to-locate observed in the present study. These factors are probably also responsible for the deterioration in performance with increasing list length observed in the present study. Nevertheless, it is remarkable that the increase of the RT with list length was consistently observed among individual subjects.

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