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Analysis of Problem Solving Process of a Mental Rotations Test – Performance in Shepard-Metzler Tasks

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Abstract. In order to clarify the ability reflected in scores in a Mental Rotations Test (MRT), the performance in Shepard-Metzler tasks (S-M tasks) was compared between experts and novices. The analysis indicated that the variety of the strategy preference in S-M tasks was very similar to that observed in the MRT. It can be said that the differences in strategies of the MRT were evoked by individual differences in performing mental rotations. The speed of mental rotation is one of the factors which have an effect on the score in the MRT. The variety of strategies for novices may be evoked by the low speed of mental rotation and the difficulty in unifying strategies to mental rotation. It is summarized that the score in the MRT evaluates the performance in mental rotations.

Key Words: spatial ability, strategy preference, individual difference

1 Introduction

Enhancement of students' spatial ability is a very important objective in early undergraduate graphics curricula. Recently, some researchers (McCuistion [4], Shiina et al. [7], Churches et al. [1]) have been interested in the relation between the ability evaluated by a Mental Rotations Test (hereafter "MRT") and graphics curricula. Although Vandenberg et al. [8], who developed the MRT, reported high correlations between the MRT and other spatial tests, it is not exactly clear which aspect of spatial ability is evaluated by the MRT.

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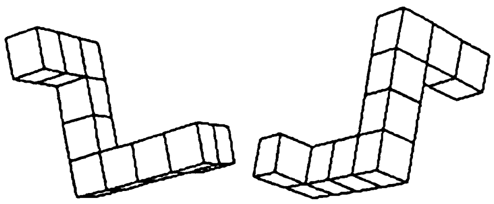
Shiina et al. [6] have analyzed the problem solving process of subjects using eye-movement records and verbal protocols, which indicate how visual information is internally manipulated. They revealed that the solving process of the MRT was classified into the following strategies: mental rotation, detecting structural features, and matching encoded descriptions. Mental rotation was the main strategy for both experts and novices. The differences of strategies between subjects were pronounced among novices. In order to explore the source of the differences in strategies of the MRT and to clarify the aspect reflected in the MRT scores, the performance in Shepard-Metzler tasks is compared between experts and novices.

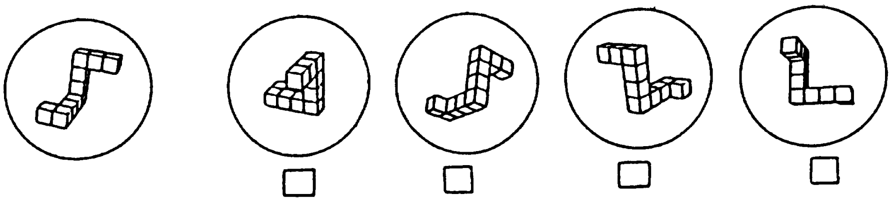
2 Experimental method

2.1 MRT and Shepard-Metzler tasks

Vandenberg et al. [8] developed the MRT based on the tasks used in an experiment made by Shepard and Metzler [5]. In Shepard-Metzler tasks (hereafter "S-M tasks"), subjects are required to determine whether two figures are views of the same three-dimensional object or not. In questions of the MRT, subjects are asked to find the two correct figures, which are identical to the criterion figure, from four alternatives. Fig. 1 shows a sample S-M task and a sample MRT question. The main difference between the S-M task and the MRT is the number of alternatives. The former requires judging whether two figures are the same or not, while the latter requires choosing from alternatives. In this paper, the S-M tasks were made by using four kinds of objects chosen from the MRT. In "Same" tasks, one figure was presented at different angle in depth from the other.



(a) Example of Shepard-Metzler tasks



(b) Sample question from MRT

Figure 1: Samples of S-M tasks and MRT

2.2 Experiment I

A cornea reflectance eye tracking system was used to monitor the eye fixations while the subjects solved the S-M tasks. The system, which was almost the same as that developed by

Makino et al. [3], was able to determine which part of each figure the subject fixated on. The solving time and the answer for each task were recorded in files by the personal computer.

12 subjects participated in experiments. 4 subjects scored 37 or 38 points (near to the full score, 40) in the preceding MRT. These subjects shall be called "experts". The other 8 subjects had low scores (less than 12 points). These subjects shall be called "novices". These experts and novices were chosen for the sake of comparison. The subject was instructed to respond as quickly as possible taking care to keep errors to a minimum. The subject responded "Same" or "Different" by clicking one of the two mouse buttons.

After solving all 20 S-M tasks, the subject was taken off the eye camera unit and required to solve 4 tasks speaking aloud. All of the verbalizations were recorded on a videotape. The transcription of this videotape –the protocols– was analyzed in addition to the eye fixation data. These protocol data were used to infer subjects' strategies together with the eye fixations records.

2.3 Experiment II

After Experiment I, the subject participated in Experiment II. The subject was instructed to solve the S-M tasks "by mental rotation". Namely, the subject was compelled to solve by mental rotation, whereas no strategy was compelled in Experiment I. The 160 S-M tasks were presented in a random order. The solving time and the answer for each task were recorded. The eye tracking system was not used in the experiment.

3 Results and discussion

3.1 Typical styles and strategies

Figs. 2–5 give sample eye fixation diagrams and corresponding S-M figures. In the diagram, the time flow is from the top of each figure down. The answer ("Same" or "Different") is indicated with the solving time. Each duration is indicated by the lengths of the vertical line. The places on the display (left and right figures) have been laid out horizontally. The numbers in the diagram correspond to those of fixation points in the figures. When the eye spot was located within $1°$ for at least 66.6 msecs., the frames were aggregated into a single fixation point. Circles in the figures show the eye fixation points. Each duration is indicated by the radius of the circle. The eye fixation diagrams may be classified into the following patterns.

3.1.1 "r"-pattern and "rn"-pattern

A typical eye fixation diagram of "r"-pattern is shown in Fig. 2. The subject repeatedly looked back and forth between the corresponding segments of each figure. The locus of the fixations moved from the upper arms to the lower arms. Such sequences resemble those of the study by Just et al. [2]. In their experiment, the mental rotation process was defined as a repeated fixation between corresponding segments. After these systematic fixations, the subject responded without repeating. The one-way scan path (from the upper arms to the lower arms) without repeat indicates a confident judgment. From the above consideration, the "r"- pattern is considered to reflect the solving process by simple and systematic mental rotation.

As shown in Fig. 3, the sequence similar to the "r"-pattern is repeated twice (0–4.8 sec. and 4.8–8.3 sec.). The diagram with multiple cycles (twice or more) of "r"-pattern is classified as an "rn"-pattern. Redundant sequences indicate that the subjects were not be able to make a complete judgment by a one-way scan path. It is considered that the "rn"-pattern reflects the solving strategy by redundant mental rotations.

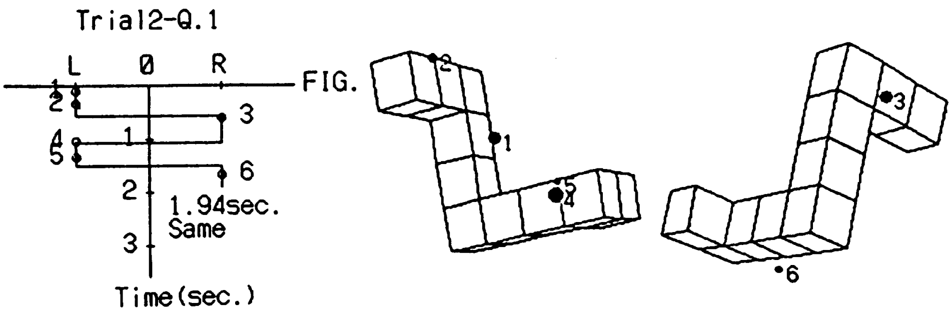


Figure 2: Typical eye fixation diagram of "r"-pattern (S13)

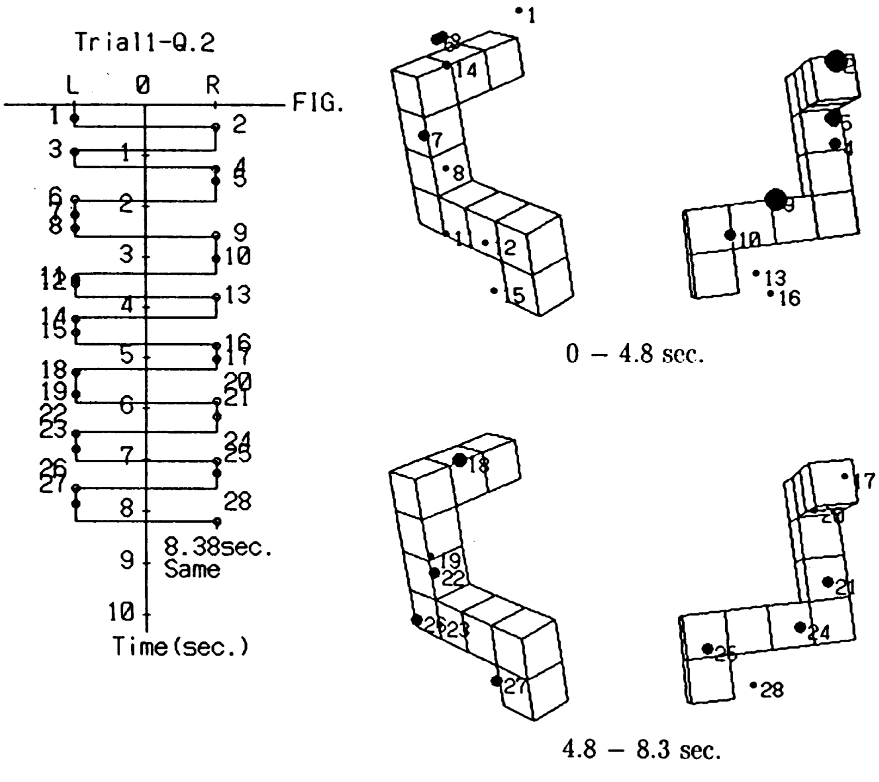


Figure 3: Typical eye fixation diagram of "rn"-pattern (S18)

3.1.2 "f/rn"-pattern

An example of eye fixation diagram of this pattern is shown in Fig. 4. After a sequence which resembles "r"-pattern (0–3.1 sec.), the consecutive fixations on one figure continued till 5.6 sec. Such partial fixations were not observed in the above-mentioned "r" and "rn"-patterns. During the relatively long duration on one figure, the locus of the fixations moved all over the entire figure. Such a sequence is classified as an "f"-pattern. After that, the pattern similar to "r" was repeated again. The diagram shown in Fig. 4 indicated "r", "f", and "r"-patterns in order, then the diagram can be labeled as an "f/rn"-pattern.

The long duration, which characterizes the "f"-sequence, is considered to indicate that the subject scanned one figure detecting for structural features. In corresponding protocol data, the subjects described the relation between the upper arm and the lower arm in figures or how the central joints are connected to each arm. It suggested that he or she had detected structural features of one figure. From the above consideration, the "f/rn"-pattern is considered to the strategy by detecting structural features together with mental rotations.

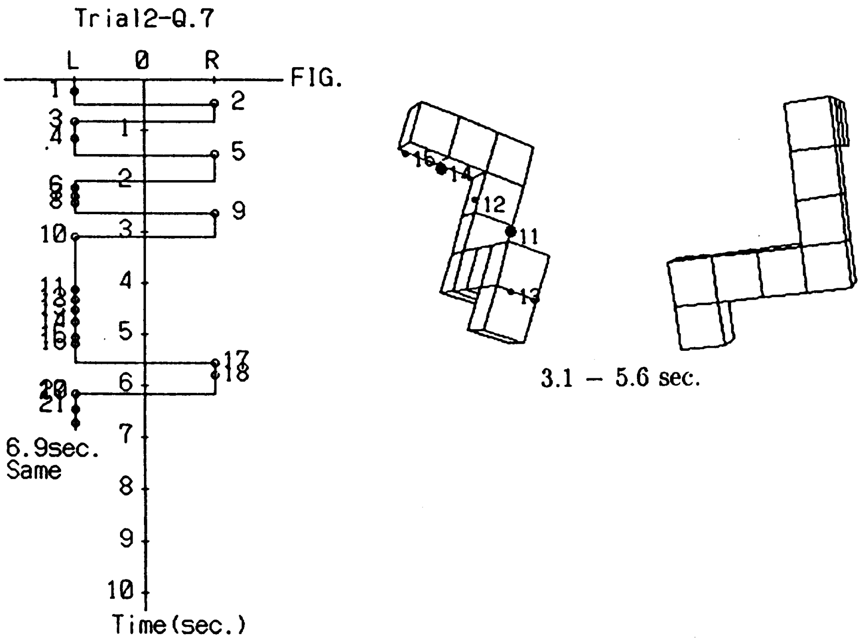


Figure 4: Typical eye fixation diagram of "f/rn"-pattern (S20)

3.1.3 "e"-pattern

A typical eye fixation diagram of this pattern is shown in Fig. 5. The long fixation times at each figure were characteristic of this diagram. For the long duration, the locus of the fixations traced the entire figure. Then a similar scan was executed on the other figure. It is considered that the subject encoded the structure of each figure in such sequences. In protocol data, the subjects whose eye fixation diagrams contained "e"-pattern reported that he had encoded the structure of each figure as if he had walked through a passage. From the above consideration, it can be concluded that the "e"-pattern corresponds to the strategy by matching encoded descriptions.

3.2 Differences of solving process between subjects

Fig. 6 shows proportions of the diagram patterns used by each subject, together with their scores in the preceding MRT. S11–S14 are experts and S15–S22 are novices.

The patterns used by the experts didn't widely differ from task to task. Most patterns used by the experts are "r" and "r1.5"-patterns. So the experts were able to make a judgment by one cycle of fixations ("r") or they needed at most a short confirmation ("r0.5") added to

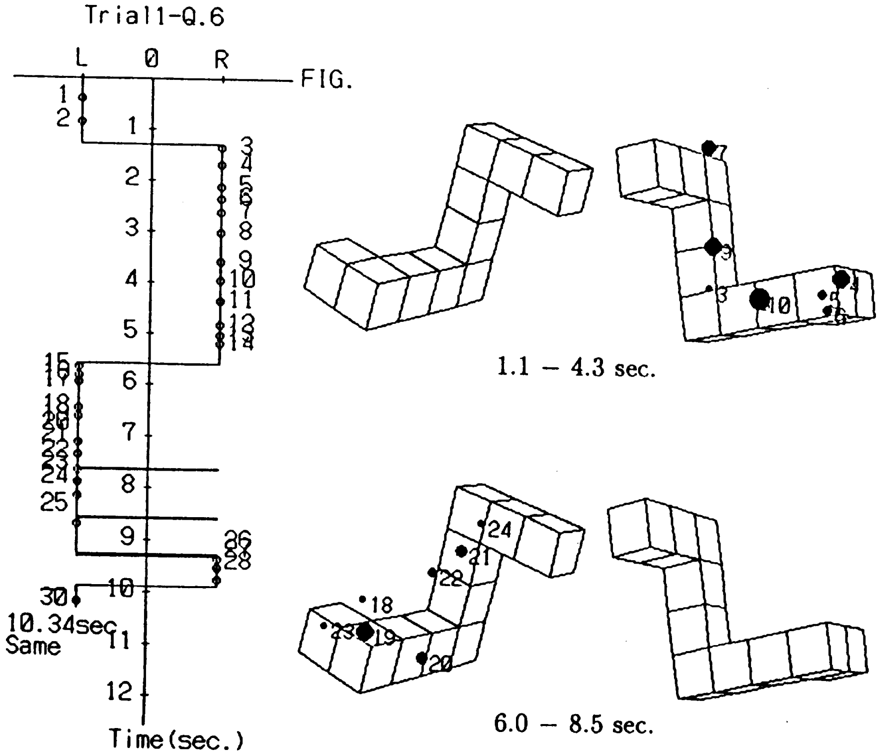


Figure 5: Typical eye fixation diagram of "e"-pattern (S19)

one cycle of fixations. The preference of "r" and "r1.5"-patterns by the experts is consistent with the fact that the experts mainly solved the MRT by simple and systematic mental rotation strategy (Shiina et al. [6]).

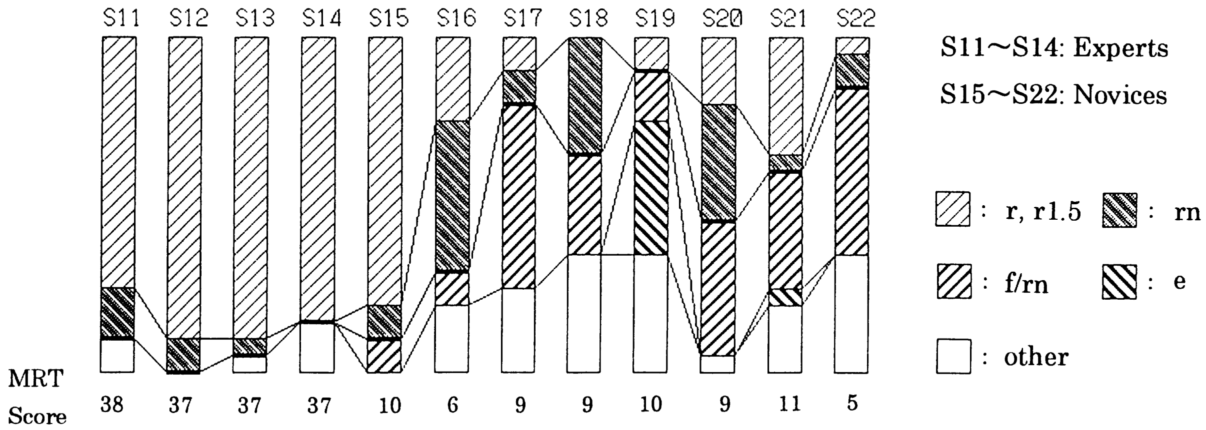


Figure 6: Proportions of diagram patterns used by each subject

The diagram patterns used by novices differed across the subjects. The preference of solving strategies for the novices are classified into following types: (1) redundant mental rotation ("rn"), (2) feature detecting together with mental rotations ("f/rn"), and (3) matching encoded descriptions ("e"). The variety of the strategy preference in S-M tasks was very similar to that was observed in the MRT by Shiina et al. [6]. The differences in strategy of the MRT remain in S-M tasks. It indicates that the differences in strategies of the MRT were not evoked by the answer style (choosing from alternatives), but by individual differences in the performance in solving S-M tasks.

3.3 Performance in mental rotation

The response times for all correct answers to "Same"-tasks were analyzed based on data of Experiment II. In Fig. 7, the response times for typical expert and novice are plotted as a function of angular disparity. Blank bars indicate error rates, which are the rates of incorrect answers for the "Same" trials for each angular disparity. For each subject, a regression line between mean response times and angular disparity was computed except for the data of 0°.

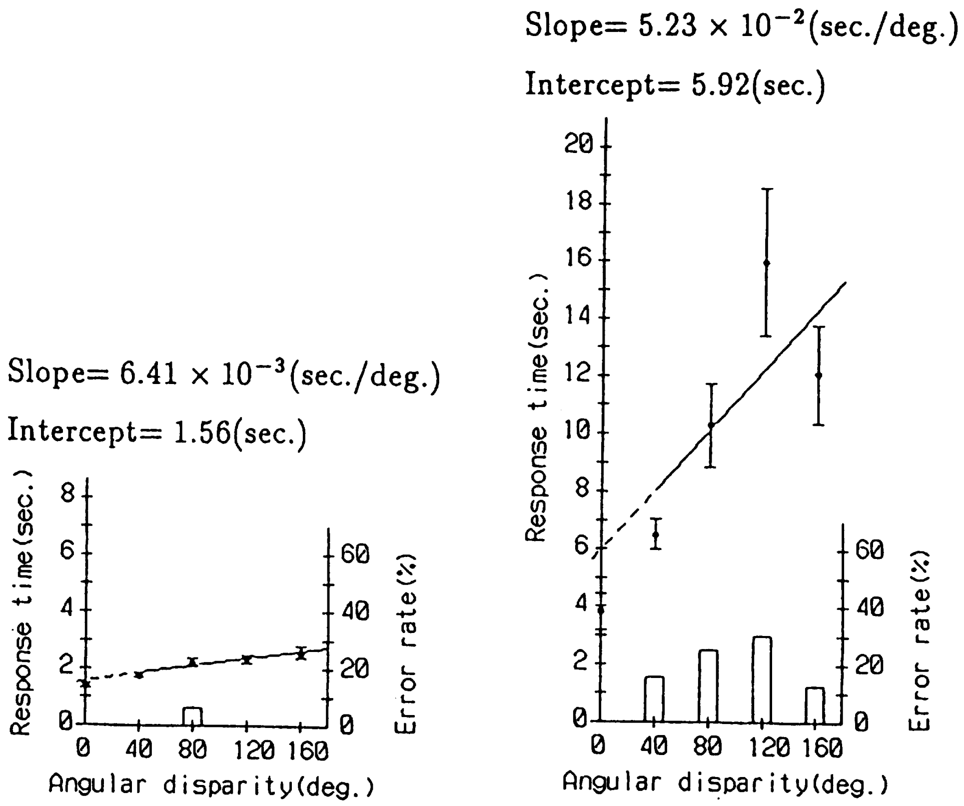


Figure 7: Response times for typical expert and novice: (a) Expert (S12), (b) Novice (S22)

In Fig. 8, the slope and the intercept of the response function for each subject (S11-S22) were summarized. A slope and an intercept of the regression line can be considered as indices of the performance in mental rotation. The parameters for the experts do not much differ between the experts. The low slopes and low intercepts show that the experts solved S-M tasks by high speed mental rotation. The high performance in the S-M tasks and stability of the strategy are bound to the high score in the MRT.

Whereas, the parameters for the novices distribute over a wide range. The wide distribution means that the difference in strategies between the novices remained even if they were compelled to solve only by mental rotation. High slopes mean the low speed of mental rotation. Subjects with low speed of mental rotations are unable to solve many questions in the limited time and will have low scores in the MRT. High intercepts indicate the existence of strategies other than mental rotation. It is difficult for some novices to solve the tasks without using strategies other than mental rotation. For subjects who use strategies other

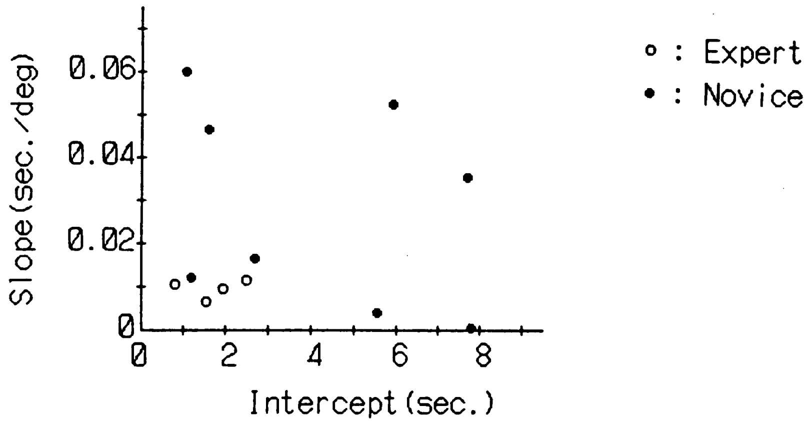


Figure 8: Slopes and intercepts for each subject

than mental rotations, it is easy to make a mistake in the MRT. The lack of the unification of strategies will also produce a low score in the MRT. Shiina et al. [6] have pointed out that such strategies other than mental rotations easily cause errors in MRT questions.

It may be induced that the low speed of mental rotation is one of the reasons for the novices' using other strategies than mental rotation. In addition to the low speed, such roundabout strategies may have much influence on novices' low performance in mental rotation.

4 Conclusion

Analysis of solving process in S-M tasks indicated that the variety of the strategy preference in S-M tasks was very similar to that observed in the MRT. It can be said that the differences in strategies of the MRT were evoked by individual differences in performance in solving S-M tasks. Simple and rapid mental rotation by experts produces a high score in the MRT and a redundant and slow rotation by some novices produces a low score. The speed of mental rotation is one of the factors which have an effect on the score in the MRT. There are some novices who show a variety of strategies to solve the MRT. The variety of strategies may be evoked by the low speed of mental rotation and the difficulty in unifying strategies to mental rotation. From the above consideration, it is concluded that the score in the MRT reflects following aspects of spatial ability; the speed of mental rotation of three-dimensional figures and the difficulty in unifying strategies to mental rotation. It is summarized that the score in the MRT evaluates the performance of mental rotation.

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