Research of Image Recognition Training Method on Manual Rendezvous and Docking

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Abstract. Astronauts may need to face a lot of complex operations and the emergency in the future space station mission. The manual rendezvous and docking image recognition training method was established based on meta-cognition in this study.

In this research, they were analyzed about the cognitive task and the image recognition process of rendezvous and docking mission. The meta-cognitive question list which help subjects to monitor their own cognitive process was designed depending on the difficulty of image recognition, then establish the meta-cognitive auxiliary training method.

By implementing metacognitive training, the following research conclusions were obtained: Metacognitive levels and self-learning results of the RVD Pictorial Handbook Test were positively correlated: Metacognitive training could effectively enhance participants' metacognitive levels and Metacognitive training could effectively enhance participants' image recognition abilities.

Keywords: Metacognition · RVD · Training · Image recognition

1 Introduction

In future space station missions, manual rendezvous and docking (RVD) operations will be one of the basic operational skills required by astronauts. Throughout this process, astronauts will need to continuously alternate between image perception and decision-making activities, and the results of each decision will provide new status information for subsequent image perception, until docking between the spacecraft and the target aerospace vehicle (AV) is complete [1, 2]. Therefore, under such cognitively demanding operational conditions, it is necessary to further build on the foundations of currently established manual RVD training to explore and establish training methods for image perception and decision-making based on metacognitive theories. This will further enhance the outcomes of manual RVD training, thus adapting to the needs of future space missions.

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2 Analysis of Manual Rendezvous and Docking Missions

The operational activities of astronauts during manual RVD missions include three components: perception of image information, decision-making on control strategy, and implementation of operational actions [5].

2.1 Perception of Image Information

The images received by the astronauts come directly from the TV camera installed on the spacecraft, which photographs the target AV from the perspective of the spacecraft [6]. The image information is then transmitted to the display on the spacecraft. As the display presents the information in the form of 2D images, the astronauts are required to reconstruct the spatial relationship between the two AVs based on the images. In other words, they need to visualize the relative positional and attitudinal relationships in 3D based on the 2D image information [4]. However, during actual operations, astronauts often make mistakes during image perception, such as judgment errors in attitudinal and directional relationships, and in spatial position relationships, which might lead to decisions to operate the wrong control levers, thus increasing fuel consumption and failures in smooth docking.

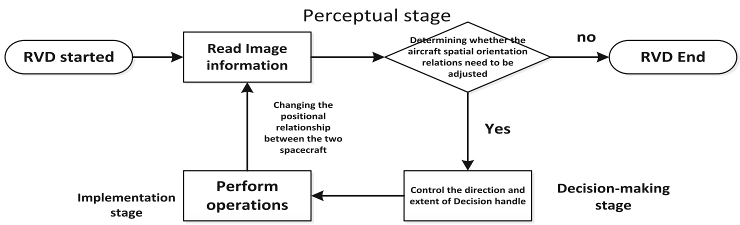

Fig. 1. The three processes of perception, decision-making, and implementation in manual rendezvous and docking [10]

2.2 Decision-Making on Control Strategies

Once the astronauts have perceived the image information, they make control decisions, which determine the selection of the control levers, as well as the direction and magnitude of the operations. The basis for decision-making stems from the spatial cognitive model formed during the perception stage, and the rules for lever control. Correct decision-making is a prerequisite and foundation of implementing operations.

2.3 Operation Implementation

The astronauts implement operational actions based on their decisions. During this process, they will perform actual operations on the control levers in order to control the spacecraft by adjusting its relative attitude and position. This process directly influences RVD outcomes (Fig. 1).

3 Training Design

Current training for manual RVD is mainly implemented through instructor teaching with excessive emphasis on the operations and operational strategies, and no in-depth coverage of the cognitive aspects. The primary focus of this study is the accuracy of image perception and operational decisions, combined with metacognitive strategies, in order to create an RVD pictorial handbook for use as training material. The RVD pictorial handbook comprises typical images acquired during the manual RVD process, and is a breakdown of the RVD process. This enables the targeted training of astronauts for missions with greater difficulty and larger deviations, as well as to improve on their weaker cognitive aspects.

3.1 Classification of Task Difficulty

Typical tasks performed during RVD operations were identified through expert interviews. Cognitive task decomposition was then used to analyze the process of perceptual judgment by the participants in order to ascertain the difficult and easy aspects of cognition. Next, the difficulty levels of the images in the RVD pictorial handbook were classified by combining the positional deviations between the AVs and the magnitude of the spacecraft yaw attitude.

3.2 Metacognitive Training Strategy

The focus of metacognitive strategies is on the participants' monitoring of their cognitive status and regulation of cognitive processes, thereby allowing them to achieve cognitive goals [3]. The two processes undertaken by astronauts when learning the pictorial handbooks (image perception and determination of operational decisions) were divided into five steps based on Gick's model of problem solving: viewing the images, re-stating the images, model placement, operation planning and implementation, and operation evaluation [9]. Metacognitive questions were designed for each step to guide the participants in planning their own problem-solving methods [8]. The participants searched for appropriate image recognition features and recognition strategies independently in order to complete judgments on the positions of the two AVs and the attitude of their own spacecraft in the images. Guidance was also provided for the monitoring of their cognitive processes (Fig. 2).

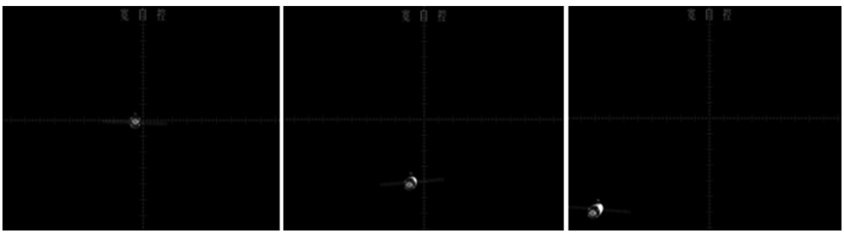

Fig. 2. Images of three different initial deviations

4 Experiment

4.1 Experimental Aims

Our aim was to investigate the effects of metacognitive training on RVD training outcomes in operators. Volunteers were recruited and assigned to either the control group, where they underwent training through independent learning, or the experimental group, where they underwent supplementary metacognitive training. Experimental research was employed to investigate the effectiveness of our training method.

A between-group design was adopted for the experiment. The independent variable was the two different training methods, and the dependent variables were the RVD image perception and decision-making abilities, and level of metacognitive ability. Perceptual and decision-making abilities were evaluated using the results of the RVD Pictorial Handbook Test.

4.2 Experimental Setup and Materials

The experimental materials required included: the Metacognition Scale, RVD Pictorial Handbook, RVD Pictorial Handbook Test, and Manual of Metacognitive Training Procedures.

(1) Manual of Metacognitive Training Procedures. By summarizing the operators' perceptions and judgment procedures during the RVD process, we developed a set of metacognitive training procedures. The metacognition group followed the related questions listed in the procedures to report their learning processes during training, including learning methods and judgment criteria, as well as their thought processes (see the Appendix for detailed procedures).

(2) Metacognition Scale. This scale was designed with reference to the Metacognitive Awareness Inventory (MAI) developed by Schraw in order to test the participants' levels of metacognition [11]. The three main dimensions included metacognitive knowledge, metacognitive awareness, and metacognitive strategies, which were intended to measure the participants' levels of metacognition.

(3) RVD Pictorial Handbook. The RVD Pictorial Handbook was used as the training material. It comprises images of the target AV acquired by the spacecraft camera at specific orbital positions during the RVD process. The participants were required to judge the positional and attitudinal information of both AVs based on the handbook (i.e., to identify whether there were translational or yaw deviations, and provide a rough judgment on the magnitude of the deviations).

(4) RVD Pictorial Handbook Test. Two sets of test papers with comparable difficulty were developed according to the knowledge of the RVD image recognition taught during training. One set was randomly selected for the pre-test and the other for the post-test.

(5) Desktop RVD Training Platform. This platform could be used to accomplish the design and development of functional modules, such as Guidance, Navigation and Control (GNC) modeling and simulation, TV image simulation, docking mechanism simulation, data storage and playback, and so forth. The platform strived for similarity between the simulated and real-world environments, and realistic modeling and simulation were performed for GNC and dynamics, docking mechanism, instruments, TV images, and other factors. The results were approved and confirmed by the project developers. The platform also took into account the flexibility requirements during experimental application; hence, the platform was equipped with functions, such as configurable experimental protocol and initial information, real-time recording of various performance data during the experiment, and complete recording and playback of experimental data and image information. This platform produced good simulation results and design, while also providing flexible configuration of experimental protocol, and accurate and complete records of experimental data. Thus, it established an excellent foundation for our experiment.

4.3 Experimental Methods

The duration of the entire experimental process lasted 60 days, and included three stages: participant selection and grouping, theoretical training, and operation implementation.

(1) Participant Selection and Grouping. Before the experiment commenced, participants were selected and asked to sign the informed consent form. Measurements of basic cognitive abilities related to RVD, metacognitive ability, and personality were then performed. Next, the participants received a general theoretical and operational explanation, and then performed a practical RVD operation. The test results were then used to evenly divide the participants into Groups A and B (i.e., experimental and control groups, respectively) according to their ability levels. Measurement of basic cognitive ability was based on the discussions of the instructors and experts with rich experience in RVD; a total of eight items were tested including: scale comparison, visual interference avoidance, judgment of spatial position, speed estimation, instrument comprehension, mental rotation, and visual changes. The Big Five Personality Test was used to measure the participants' personality traits, and screening was performed. Metacognitive ability was measured using the Metacognition Scale, which was modified from the MAI developed by Schraw. The participants were randomly divided into two groups based on their metacognitive ability and individual items of cognitive ability.

(2) Theoretical Training. Before implementing the experiment, the chief astronaut instructor provided theoretical training on RVD techniques and operational strategies to beginner-level participants. Next, the participants performed three practical operational exercises on the RVD training platform under the real-time supervision of the main experimenter. Through the practical exercises, participants were able to master basic image recognition skills, as well as operational methods and strategies. They had essentially achieved the skill requirements of manual RVD operations (Fig. 3).

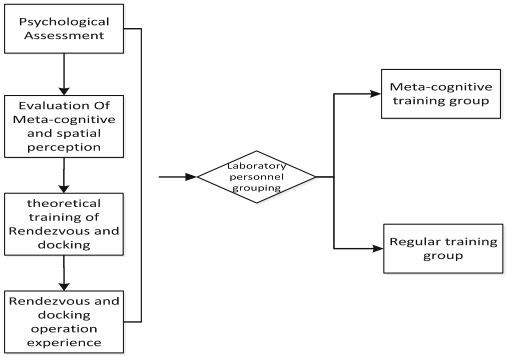

Fig. 3. Workflow of experimental preparations

(3) Experimental Implementation. The RVD training experiment formally began at the end of theoretical training. In this stage, participants in the experimental and control groups received five rounds of RVD training; each round involved 30 min of RVD Pictorial Handbook self-learning, and six sessions of manual RVD operations. During the 30 min training with the RVD Pictorial Handbook, the experimental group use the Manual of Metacognitive Training Procedures during learning, whereas the control group only undertook self-learning. After the completion of the training experiment, post-testing of metacognitive levels, as well as manual RVD image perception and decision-making abilities were performed in both groups (Fig. 4).

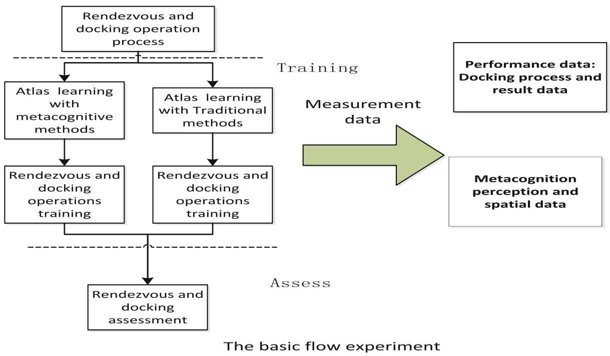

Fig. 4. Basic experimental flow

5 Experiment Results and Analysis

5.1 Pre-test Descriptive Statistics of Relevant Variables

In the experimental design, the control group learned the materials of the RVD Pictorial Handbook through independent learning. Next, they undertook the RVD Pictorial

Handbook Test, and obtained their results. The metacognitive levels were also measured before and after training using the Metacognition Scale. Correlational analysis was then performed on the results.

As shown in Tables 1 and 2, participants' metacognitive levels and self-learning outcomes of the RVD Pictorial Handbook showed a significantly positive correlation ($P < 0.01$). This indicates that after independent learning, participants' self-learning results and their existing levels of metacognition were closely related. Participants with higher levels of metacognition were able to obtain better results on the RVD Pictorial Handbook test after independent learning; participants with lower levels of metacognition scored less well on the test after independent learning of the RVD Pictorial Handbook.

Table 1. Participants' existing metacognitive levels and self-learning results

Variable	Mean	SD	Minimum	Maximum	Kurtosis
Metacognitive level	57.20	7.73	44.86	70.93	−0.744
Test results	27.63	13.72	9.09	55.68	−0.738

Table 2. Correlational analysis of participants' metacognitive levels and test results

	Pictorial handbook test results
Metacognitive level	0.700**

5.2 Difference Testing of Pre- and Post-Test Metacognitive Levels and RVD Pictorial Handbook Test Scores in the Experimental and Control Groups

(1) Difference testing of pre- and post-test metacognitive levels and self-learning results in the control group

During the experiment, the control group undertook independent learning when the experimental group was undergoing metacognitive training. Difference testing of pre- and post-test metacognitive levels and self-learning results of the control group can be found in the tables below (Fig. 5).

As shown in Tables 3 and 4, when $t = -1.96$, $P = 0.847$ ($P > 0.05$); hence, there was no significant difference between the pre- and post-test results for the participants' metacognitive levels in the control group. Furthermore, when $t = -1.831$, $P = 0.082$ ($P > 0.05$); hence, the difference between the pre- and post-test results of the RVD Pictorial Handbook self-learning was not significant in the control group (Fig. 6).

(2) Difference testing of pre- and post-test metacognitive levels and self-learning results in the experimental group

As shown in Tables 5 and 6, when $t = -2.994$, $P = 0.009$ ($P < 0.05$); hence, there was a significant difference between the pre- and post-test results of the metacognitive levels in the experimental group. Furthermore, when $t = -3.798$, $P = 0.02$ ($P < 0.05$);

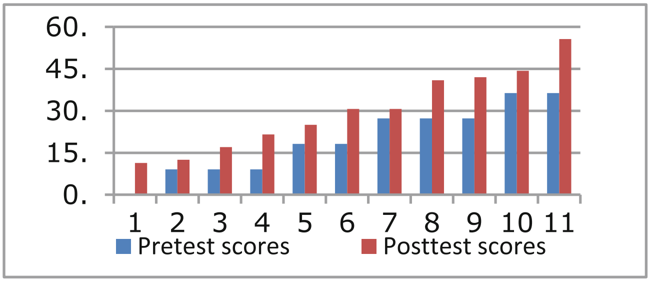

Fig. 5. Pre- and post-test results of the RVD Pictorial Handbook self-learning in the control group

Table 3. Difference testing of pre- and post-test self-learning results in the control group

	Group	Mean score	SD	t	P
Test results	Pre-test results	19	12.07	−1.831	0.082
	Post-test results	30	14.30		

Table 4. Difference testing of pre- and post-test metacognitive levels in the control group

	Group	Mean score	SD	t	P
Metacognitive level	Pre-test results	57.50	8.09	−1.96	0. 847
	Post-test results	58.18	7.90		

hence, the difference between the pre- and post-test results of the RVD Pictorial Handbook Test was significant in the experimental group. This indicates that after the participants in the experimental group undertook metacognitive training, their metacognition and self-learning results of the RVD Pictorial Handbook improved significantly.

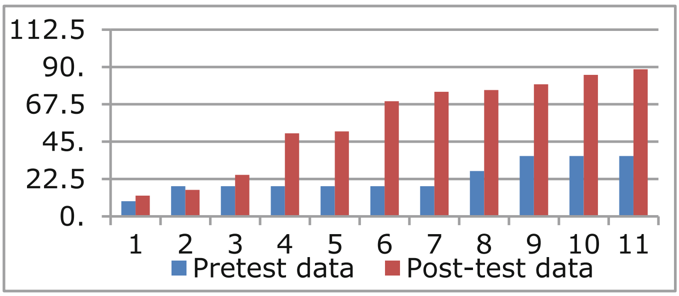

Fig. 6. Pre- and post-test results of the RVD Pictorial Handbook self-learning in the experimental group

Table 5. Difference testing of pre- and post-test self-learning results in the experimental group

	Group	Mean score	SD	t	P
Test results	Pre-test results	23.14	9.41	−3.798	0.02
	Post-test results	57.13	28.15		

Table 6. Difference testing of pre- and post-test metacognitive levels in the experimental group

	Group	Mean score	SD	t	P
Metacognitive level	Pre-test results	59.21	7.16	−2.994	0.009
	Post-test results	72.66	13.05		

5.3 Analysis of Post-Test Metacognitive Levels and the RVD Pictorial Handbook Test Results

(1) Difference testing of the post-test metacognitive levels

The metacognitive levels of participants in the experimental and control groups were measured again after training, and difference testing was performed on the post-test results (Table 7).

Table 7. Difference testing of post-test metacognitive levels

	Group	Mean score	SD	t	P
Metacognitive level	Experimental group	72.66	13.05	2.93	0.011
	Control group	60.14	5.46		

As shown in Table 7, for the post-test metacognitive levels, when $t = 2.93$, $P = 0.011$ ($P < 0.05$); this indicates that the metacognitive levels after training in the experimental group were significantly higher than that of the control group. Targeted training of metacognitive skills was performed during the training process, such as guiding the participants in formulating plans for image recognition, regulating learning strategies, monitoring their own cognitive status, and reflecting on the shortcomings in their own cognition. These skills also formed the basic content of the Metacognition Scale. Hence, after a period of training, the experimental group showed significantly better performance than the control group (Fig. 7).

(2) Difference testing of the post-test RVD Pictorial Handbook test results

The RVD Pictorial Handbook Test was performed in the experimental and control groups after training, and difference testing was performed on the post-test results (Table 8).

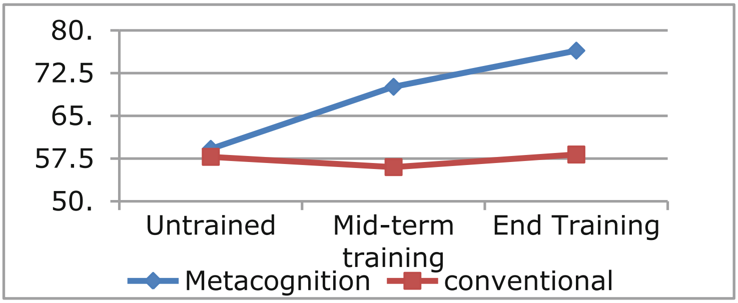

Fig. 7. Plot of changes in the metacognitive ability in both groups

Table 8. Difference testing of the post-test RVD Pictorial Handbook self-learning results

	Group	Mean score	SD	T	P
Results	Experimental group	72.66	13.05	2.93	0.011
	Control group	60.14	5.46		

As shown in Table 8, when t = 2.93, P = 0.011 ($P < 0.05$). After metacognitive training, the RVD self-learning results of the experimental group were significantly higher than those of the control group. This indicates that metacognitive training could effectively enhance the results of the RVD Pictorial Handbook Test. During RVD perceptual and operational training combined with the RVD Pictorial Handbook, targeted participant training was achieved. This included cultivating independent thinking, image analysis, self-reporting on the processes during image perception to operational decision-making, spatial imagination, and self-learning ability (Fig. 8).

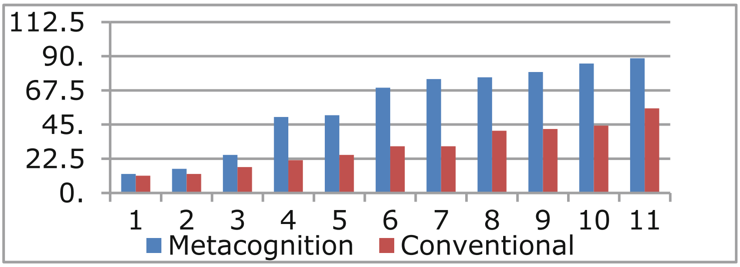

Fig. 8. Post-test learning results of the experimental and control groups

6 Conclusions and Discussion

By implementing metacognitive training, the following research conclusions were obtained:

6.1 Metacognitive Levels and Self-Learning Results of the RVD Pictorial Handbook Test Were Positively Correlated

Participants with high metacognitive levels had a better grasp of the knowledge of interpreting the images in the RVE Pictorial Handbook, and their success rates for the test questions were also higher. This implies that their self-learning outcomes were better. Therefore, increasing metacognitive levels could increase their self-learning outcomes.

6.2 Metacognitive Training Could Effectively Enhance Participants' Metacognitive Levels

After a period of metacognitive training in the experimental group, their metacognitive levels were significantly higher than those of the control group. This also indicates that the metacognitive levels of the experimental group had improved significantly, which once again verifies that performing metacognitive training during the learning process of the RVD Pictorial Handbook was effective.

6.3 Metacognitive Training Could Effectively Enhance Participants' Image Recognition Abilities

The self-learning results for the RVD Pictorial Handbook Test were performed on both groups before the experiment; the between-group difference in the test results was not significant. However, after a period of RVD training, the post-test determined that the test results of the experimental group were significantly higher than those of the control group, and the between-group difference was significant. This implies that metacognitive training significantly enhanced the RVD image interpretation abilities of the experimental group.

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