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Trend Analysis of Cognitive Ability in Three Long-Duration Working Groups Based on Piecewise Linear Regression

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ABSTRACT

Long-duration operations in confined and shift-based environments can significantly affect operator cognitive ability. This study investigates the trends of cognitive ability changes in three long-duration working groups using piecewise linear regression. Fifteen participants were divided into three shift groups (A1, A2, and A3) and completed a 288-hour simulated monitoring task. Cognitive ability was assessed before and after each duty period through five indicators: perceptual stability, attention-and-vigilance stability, working-memory stability, reasoning-and-decision stability, and executive-function stability. Group-level cognitive ability time series were constructed by averaging the five normalized indicators, and two-segment linear models were fitted to capture the overall trend of cognitive changes over time. The results show that all three groups exhibited an overall declining trend with local fluctuations and partial recovery, while the magnitude and pattern of changes varied according to shift timing. Group A2 maintained the highest overall cognitive ability level, whereas Group A3 showed the lowest among the three groups. The piecewise linear regression models achieved low root-mean-square errors for all groups, indicating good fitting accuracy and stability. These findings suggest that shift timing influences the trend of cognitive ability during long-duration operations, and the proposed piecewise linear regression approach can effectively describe the temporal dynamics of cognitive performance.

Keywords: Cognitive ability evaluation, Long-duration operation, Linear regression model

INTRODUCTION

In long-duration confined missions such as manned spaceflight and deep-sea exploration, maintaining cognitive ability is critical for safety and efficiency. Operators work continuously for long periods under isolated conditions, and prolonged circadian disruption can cause sleep disorders and cognitive declin. Core functions such as perception, attention, working memory, decision-making, and executive function directly determine task performance. Studies show that prolonged operations lead to slower reactions, more errors, and reduced vigilance, and shift work further impairs cognitive function. In such missions, even a single error can have severe consequences.

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Most existing cognitive prediction methods are designed for ordinary work environments and provide only static assessment of short-term or single-session data. There is limited research on long-duration, confined, shift-based settings, where stressors such as circadian disruption and isolation are prominent. Because cognitive ability changes dynamically and is influenced by multiple interacting factors, methods developed for conventional workplaces cannot be directly applied to long-duration confined operations.

Cognitive ability is typically assessed through several dimensions: perceptual stability (speed-perception test), attention and vigilance (PVT), working memory (n-back tasks), reasoning and decision-making (BART), and executive function (Stroop test). Existing analytical approaches mainly include statistical regression, physiological threshold judgment, and task-performance analysis. Although simple and interpretable, these methods are mostly static, assume independence among influencing factors, and ignore individual differences and temporal dynamics. As a result, they cannot adequately capture the continuous variation of cognitive ability over long tasks.

This paper proposes a trend analysis method based on piecewise linear regression. First, key influencing factors and cognitive indicators are identified through causal analysis. Then, a 288-hour simulated-task experiment is conducted with 15 participants divided into three shift groups. Finally, two-segment linear models are fitted to the cognitive ability time series, and the fitting accuracy is evaluated using the root-mean-square error. The proposed approach provides a simple and effective way to describe the overall decline-recovery trend of cognitive performance in long-duration, confined, shift-based operations.

METHODS

Cognitive Ability Variations of Long-Duration Operators

Cognitive ability refers to the fundamental capacity of operators to perceive environmental changes and acquire task-relevant information during prolonged operations. Information processing comprises perceptual encoding, attentional allocation, memory operations, decision-making, and response execution. Since cognitive ability emerges from multiple causal factors, the present study characterizes it through five key indicators.

Factors Influencing Cognitive Ability

Based on an examination of the working environment, shift schedule, and individual state of operators during long-duration tasks, several factors are considered to contribute to cognitive decline. First, confinement duration is selected as an influencing factor because operators perform tasks for extended periods in confined and isolated settings, where the psychological and physiological demands of prolonged confinement can disrupt daily routines and working states, thereby affecting cognitive performance. Second, the shift cycle is considered through two indicators-shift timing and daily cumulative work hours-since long-duration operators work in

groups across different time periods to ensure 24-hour coverage, and the organization of shift schedules influences cognitive ability. Third, circadian rhythm and sleep are represented by pre-shift sleep duration and circadian arousal level, as biological rhythms and sleep quality directly affect alertness, emotional state, fatigue, and cognitive functioning. Finally, the working environment is characterized by noise level, CO_2 concentration, illuminance, and lighting color temperature, because these environmental factors differ from ordinary workplaces and influence psychological and physiological states.

Key Cognitive Abilities

(1) Perceptual stability. This indicator reflects the ability to receive external stimuli through visual, auditory, and tactile channels during task execution. It is assessed by examining sensory sensitivity and perceptual constancy, indicating whether perceptual quality remains stable when environmental conditions change.
(2) Attention-and-vigilance stability. This indicator captures the ability to sustain focused attention and remain alert to critical signals over extended periods. It encompasses attentional persistence, selectivity, resistance to distraction, and fluctuations in vigilance.
(3) Working-memory stability. This indicator measures the capacity to temporarily store, manipulate, and update information during task performance. Its stability reflects how well working-memory capacity and processing efficiency are maintained as task duration and workload vary.
(4) Reasoning-and-decision stability. This indicator describes the degree to which logical reasoning, option evaluation, and judgment remain consistent under complex or uncertain conditions as task time increases. It considers changes in decision speed, accuracy, and strategy consistency.
(5) Executive-function stability. This indicator concerns the higher-order control processes involved in planning, monitoring, regulating, and flexibly shifting one's own cognitive operations. Task management, error monitoring, inhibitory control, and cognitive flexibility are all influenced by executive functioning.

These five indicators serve as the cognitive ability variables.

(1) Perceptual stability is measured by the speed-perception test.
(2) Attention-and-vigilance stability is measured by the PVT.
(3) Working-memory stability is measured by the 2-back test, including verbal and spatial versions.
(4) Reasoning-and-decision stability is measured by the BART.
(5) Executive-function stability is measured by the color-word Stroop test.

Indication Quantification

Before and after each duty period, participants are assessed on five dimensions: perceptual stability, attention-and-vigilance stability, working-memory stability, reasoning-and-decision stability, and executive-function stability. These dimensions are denoted as g_1~g_5, respectively.

To eliminate the influence of differing dimensions and value ranges among the test indicators, the raw reaction-time results of each test are normalized; accuracy is already within the range of 0~1. The lower and upper bounds (min/max) used for normalizing each indicator are summarized in Table 1.

Table 1: Normalization parameters of reaction-time test results.

No.	Test	Max	Min
g_1	Speed-perception test	900	250
g_2	PVT test	1000	200
g_3	2-back verbal & spatial memory test	1800	650
g_4	BART test	70	10
g_5	Color-word Stroop test	1000	350

EXPERIMENTS

To examine how cognitive ability changes over the course of a prolonged task and to assess the proposed model, a simulated operational experiment was carried out with 15 participants. The entire experiment lasted 15 days: the first 3 days were used for participant training, and the remaining 12 days constituted the formal experimental period, totaling 288 hours.

Participants were assigned to three shift groups according to their duty schedules, designated A1, A2, and A3. Each group was required to complete two work sessions per day, and the specific duty periods are summarized in Table 2.

Table 2: Duty schedule of the three groups.

Group	Duty Period 1	Duty Period 2
A1	00:00–04:00	12:00–16:00
A2	04:00–08:00	16:00–20:00
A3	08:00–12:00	20:00–24:00

With this arrangement, at least one group was on duty at any given time during the day. Outside their assigned work periods, participants were allowed to rest or engage in leisure activities. The experimental protocol was approved by the Institutional Review Board (IRB) of Beihang University.

The task scenario was designed to simulate a typical monitoring operation and included four successive subtasks: perception, comprehension, prediction, and decision. Before and after each duty session, participants completed five cognitive assessments: the speed-perception test, the PVT, verbal and spatial 2-back tests, the BART, and the color-word Stroop test. Throughout the experiment, the working environment was continuously recorded, and mental-state questionnaires and physiological measures were collected at fixed intervals. The measurement platform is illustrated in Figure 1.



Figure 1: Measurement platform.

RESULTS AND DISCUSSION

Experimental Measured Results of Cognitive Ability

For each group, the experimental cognitive ability level, Prexi (i = 1,2,3), is obtained by averaging the five indicator results (G_1~G_5) with equal weights across participants within the group. The measured cognitive ability data for the three groups (A1, A2, and A3) are presented in Figure 2~4.

Cognitive Ability Level Variation of Group A1

Group A1 worked in the shift timings of 00:00-04:00 and 12:00-16:00 over the 12-day experimental period. The cognitive ability level variation of Group A1, obtained by averaging the post-experimental data of participants within the group and then applying equal-weight weighting to the G_1~G_5 results, is shown in Figure 2.

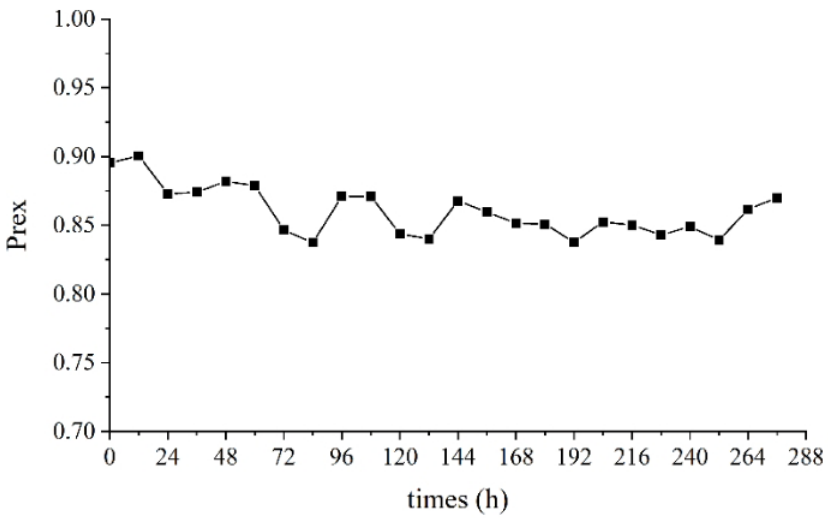


Figure 2: Cognitive ability level variation of Group A1.

As shown in Figure 2, the variation of cognitive ability level of Group A1 fluctuates within the range of 0.83 to 0.9, with an overall declining trend despite local fluctuations. In the early stage of the experiment (0~96h), cognitive ability first decreased from 0.9 to about 0.83, a drop of approximately 7.78%, and then rose to 0.87. During the middle stage (96~192h), it first declined from 0.87 to 0.84, then rose to 0.86, and subsequently decreased gradually to 0.84, a drop of about 2.33%. In the later stage (192~288h), the values remained relatively stable at around 0.85, with a rise from 0.84 to 0.87 at 252 h, an increase of about 3.57%.

Cognitive Ability Level Variation of Group A2

Group A2 worked in the shift timings of 04:00~08:00 and 16:00~20:00 over the 12-day experimental period. The measured cognitive ability variation for Group A2, obtained by averaging the post-experimental data of participants within the group and then applying equal-weight weighting to the G1~G5 results, is shown in Figure 3.

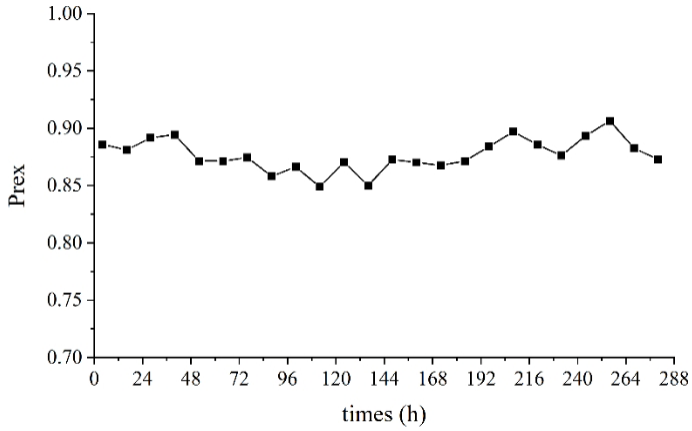


Figure 3: Cognitive ability level variation of group A2.

As shown in Figure 3, the cognitive ability level variation of Group A2 fluctuates within the range of 0.85 to 0.91, with an overall trend of first declining and then rising. In the early stage of the experiment (0~96h), cognitive ability decreased from 0.89 to approximately 0.86, a drop of about 3.37%. During the middle stage (96~192h), the overall trend was upward, with cognitive ability rising from 0.87 to about 0.89, an increase of about 2.25%. In the later stage (192~288h), cognitive ability showed fluctuating changes: it first decreased from 0.9 to 0.87, then rose to 0.91, and finally declined gradually to 0.87.

Cognitive Ability Level Variation of Group A3

Group A3 worked in the shift timings of 08:00~12:00 and 20:00~24:00 over the 12-day experimental period. The cognitive ability level variation of Group A3, obtained by averaging the post-experimental data of participants

within the group and then applying equal-weight weighting to the G1~G5 results, is shown in Figure 4.

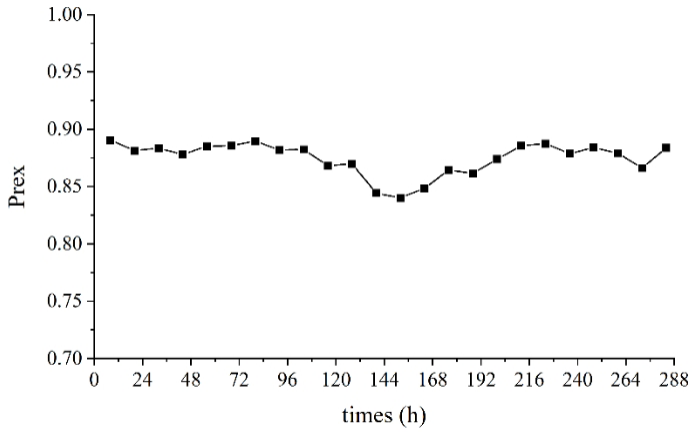


Figure 4: Cognitive ability level variation of group A3.

As shown in Figure 4, the cognitive ability level variation of Group A3 fluctuates within the range of 0.85 to 0.90, with an overall trend of first declining and then rising. In the early stage of the experiment (0~96h), cognitive ability decreased from 0.88 to approximately 0.87, a drop of about 1.14%. During the middle stage (96~192h), it first declined from 0.87 to 0.84, a decrease of about 3.45%, and then rose gradually to 0.86, an increase of about 2.38%. In the later stage (192~288h), cognitive ability first rose gradually from 0.86 to 0.90, an increase of about 4.65%, and then showed fluctuating declines.

Among the three groups, Group A2 exhibited the highest overall measured cognitive ability level, while Group A3 showed the lowest. Group A1 displayed an overall declining trend. Group A2 showed relatively stable fluctuations within its variation range. Group A3 clearly showed a pattern of first declining and then rising. Overall, all three groups exhibited a trend of first declining and then rising.

Trend Analysis

To analyze the changing trends in cognitive ability levels, this trend model was generated by applying conventional group-wise piecewise linear regression to the experimental data. For each group, we computed the mean measured cognitive value at each time point and fitted a two-segment linear model of the experiment. This conventional baseline model can also capture the overall "decline-then-recovery" trend commonly observed in cognitive research, without incorporating probabilistic inference or individualization. In this study, the model results are represented as Pr_i. Table 33 presents the fitted linear models for the three groups, where x denotes time, h.

Table 3: Two-segment linear models for groups.

Groups	First-Segment	Second-Segment
Group A1	$Pr_1 = -0.006x + 0.898$	$Pr_1 = -0.000x + 0.854$
Group A2	$Pr_2 = -0.004x + 0.892$	$Pr_2 = 0.002x + 0.837$
Group A3	$Pr_3 = -0.004x + 0.885$	$Pr_3 = 0.003x + 0.806$

The predicted cognitive ability level variations for the three groups were obtained, as shown in Figure 5. Each figure presents a three-curve comparison among Pr_1~Pr_3.

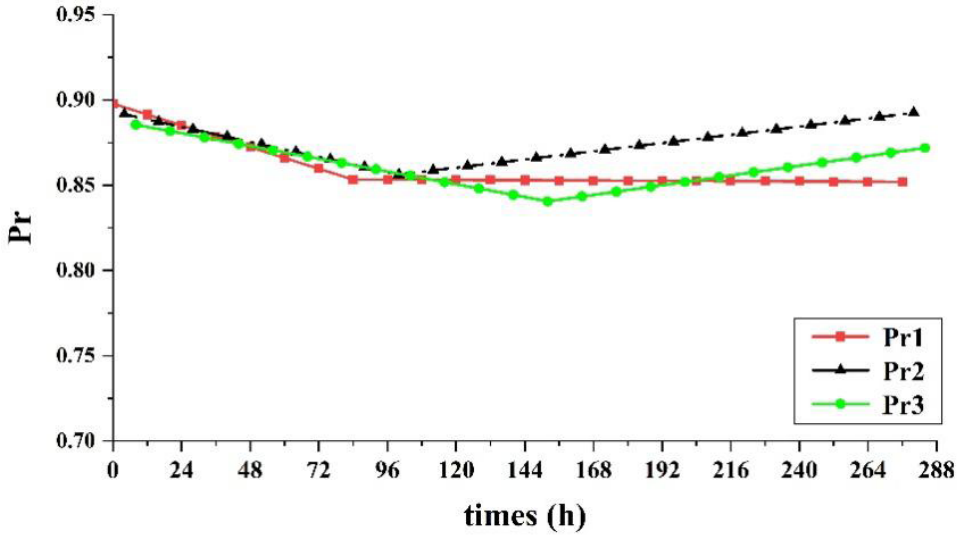


Figure 5: Comparison of Pr_1~Pr_3.

As shown in Figure 5, the initial cognitive ability levels of all three groups were approximately 0.9. For Group 1, Pr_1 reached its minimum value of 0.853 at 84 h, then gradually decreased to 0.852, representing a decline of about 0.12%. For Group 2, Pr_2 reached its minimum value of 0.856 at 100 h, with a decrease of approximately 4.89%, and then gradually increased to 0.89, representing an increase of about 3.97%. For Group 3, Pr_3 reached its minimum value of 0.841 at 152 h, with a decrease of approximately 0.656%, and then increased to 0.872.

Among the three groups, Group A2 exhibited the highest overall predicted cognitive ability level, while Group A3 showed the lowest. Group A1 displayed an overall declining trend, with a slight recovery in the later stage. During the middle phase of the experiment, the cognitive performance of all three groups successively declined to their respective lowest levels of that stage, and then gradually rebounded. Group A1 reached this nadir first, followed by Group B, and Group C last; thereafter, each group showed a steady recovery during the mid-to-late stages of the experiment.

The RMSE can evaluate the fitting stability and robustness against fluctuations. A smaller RMSE indicates smaller deviation variability. It is calculated as:

$$RMSE = \sqrt{\frac{1}{N}\sum_{t=1}^{N}(Pr_t - Prex_t)^2}$$

where $Prex_t$ and Pr_t are the *t-th* overlapping samples of the measured sub-sequence and the predicted sub-sequence, respectively, and Prex and Pr are their respective means.

The RMSE values for all three groups are 0.011, 0.007 and 0.01. In all three groups, the two-segment linear models consistently achieve the low errors

Study Limitations and Future Work

Several limitations of this study should be acknowledged. First, each shift group comprised only five participants, which limits the statistical power of the analysis and precludes formal significance testing for group differences. Therefore, the observed differences in cognitive trajectories among the three groups should be interpreted as preliminary observations rather than definitive causal conclusions. Additionally, factors such as chronotype and sleep habits were not systematically controlled, which may contribute to inter-individual variability. Nevertheless, all participants were recruited under a uniform protocol and maintained consistent living, meal, and rest schedules throughout the experiment, which helped mitigate the influence of lifestyle and environment.

CONCLUSION

This study examined changes in cognitive ability among long-duration operators working under confined and shift-based conditions. Five cognitive indicators were used to represent key abilities: perceptual stability, attention-and-vigilance stability, working-memory stability, reasoning-and-decision stability, and executive-function stability. The temporal trend of cognitive ability was described using two-segment linear models. A 288-hour simulated task experiment was conducted with 15 participants assigned to three groups (A1~A3) under different shift schedules.

The results indicate that the cognitive ability of all three groups showed an overall downward trend over the 12-day experimental period, accompanied by local fluctuations and partial recovery that differed according to shift timing. Group A2, which worked during 04:00~08:00 and 16:00~20:00, maintained the highest overall cognitive ability level, ranging from approximately 0.85 to 0.90. Group A3, with duty periods of 08:00~12:00 and 20:00~24:00, exhibited the lowest level, ranging from approximately 0.84 to 0.89. The fitted two-segment models produced RMSE values of approximately 0.01 for all groups, indicating that the piecewise linear approach provided stable and numerically accurate descriptions of the observed cognitive trends.Overall, the proposed method is effective for capturing the general decline-recovery

pattern of cognitive performance during long-duration operations, and shift timing appears to influence both the level and trajectory of cognitive ability over time.

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