Exploring Animal Behavior Models from an Integrative Learning Perspective

Authors: Yin Bin, WU Xiaorui, Lian Rong, Lian Rong

Date: 2020-07-19T00:00:00+00:00

Abstract

The prevailing learning paradigm in contemporary China emphasizes incremental learning. The present research proposes a learning paradigm of "integrative learning," employing 40 SD rats as subjects in a 2 (learning method: integrative/incremental) × 2 (sex: male/female) between-subjects design, and utilizing a 14-unit composite T-maze to conduct five-stage animal behavior modeling. The results showed that: (1) in terms of learning error counts, the integrative group made fewer errors than the incremental group, and males made fewer errors than females; (2) the integrative approach demonstrated better transferability of learning effects compared to the incremental approach; and (3) all groups exhibited perseveration on the originally correct path in the first segment. These findings indicate that integrative learning yields more durable effects, and that acquired knowledge exhibits transferable characteristics of holism, chunking, and categorization.

Full Text

Exploring an Animal Behavioral Model of the Integrated Learning Concept

YIN Bin, WU Xiaorui, LIAN Rong
School of Psychology, Fujian Normal University, Fuzhou, Fujian 350108, China

Abstract

The current learning concept in China is dominated by progressive learning. This study proposes an "integrated learning" concept and explores it through animal behavior modeling. Forty SD rats were used as subjects in a 2 (learning method: integrated/progressive) × 2 (sex: male/female) between-subjects design. A 14-unit composite T-maze was employed across five stages of behavioral modeling. Results showed: (1) In terms of learning errors, the integrated group made fewer errors than the progressive group, and males made fewer errors than females; (2) The integrated learning approach demonstrated better transferability of learning effects compared to the progressive approach; (3) All groups exhibited fixation on the originally correct first path segment. These findings suggest that integrated learning is more effective in the long term, and the acquired knowledge exhibits characteristics of wholeness, chunking, and categorization that facilitate transfer.

Keywords: integrated learning concept; animal behavioral model; maze test
Classification Codes: B842.3 & B843.2

1 Introduction

Learning concept refers to students' intuitive understanding of knowledge, learning phenomena, and experiences (刘儒德, 2002). As human society has entered the information age and era of artificial intelligence (post-industrial, postmodern society), traditional learning concepts can no longer adequately explain the changing phenomena of learning in the new era. There is an urgent need to discover new components of student learning psychology based on new developments and research (施良方, 2000). Since the emergence of school education accompanying the industrial revolution, student learning has consistently emphasized a step-by-step, part-to-whole approach. In an era of relative knowledge scarcity and limited access pathways, this learning method suited its context. However, as we enter an era of abundant knowledge and diverse access channels, the inherent problems of this approach have become increasingly apparent, most notably the continuously growing learning burden and pressure on students. Although various educational reforms have targeted this issue for improvement, students' learning burden has only increased. The root of the problem lies in our lack of new understanding of learning phenomena that have undergone qualitative changes.

Based on this, we propose the integrated learning concept: "Integrated learning" refers to a process where, under the function of metacognition, cognition actively integrates learning materials to achieve efficient and in-depth understanding and mastery of knowledge—a learning psychological process where metacognition and cognition are highly unified. Correspondingly, non-integrated learning (such as progressive learning) emphasizes a cognitive-level, actively progressive understanding and mastery of knowledge from parts to whole. The main difference between these two learning concepts is that integrated learning emphasizes a psychological mechanism where metacognition and cognition are highly unified, whereas non-integrated learning emphasizes cognitive learning psychological mechanisms.

Do these differences in learning concepts have a biopsychological basis? Animal behavior research and teaching help us understand the fundamental principles underlying behavior and provide convenient, highly controlled models for humans (朱滢, 2019). Therefore, to understand the impact of the integrated learning concept on learning outcomes and further find corresponding neurophysiological evidence, we must first conduct animal behavior modeling research, just as Thorndike did when proposing connectionist learning theory (张厚粲, 2003), Skinner did when proposing operant conditioning and reinforcement theory (Skinner, 1945; see also 周正怀, 2005a, 2005b), and Tolman did when proposing "cognitive map" theory and first introducing intervening variables in psychological research (Tolman, 1948). By studying rats' integration process of maze path information (王彦 & 苏彦捷, 2001), we can obtain fundamental theoretical insights and provide evolutionary and developmental evidence for elucidating the characteristics, effects, and internal mechanisms of the integrated learning concept.

We adapted and modified Tolman' s (1948) 14-unit composite T-maze. The integrated learning method was operationally defined as "a learning method where rats, based on overall grasp of the maze path, actively integrate path information with internal cognition to efficiently acquire transferable path information." The progressive learning method was operationally defined as "a learning method where, based on the transferable patterns of maze paths, the maze is rigidly planned in terms of path segments and time course, gradually increasing rats' learning material capacity and transferable information." The reason for these definitions is that the essential characteristic of integrated learning is the high unification of metacognition and cognition in students' knowledge acquisition process. Schraw (1998) proposed that metacognition is cognition about cognitive processes, with both cognitive and monitoring dimensions. Therefore, under the integrated learning concept, learners engage in "whole-part-integration" learning under metacognitive monitoring, whereas progressive learning, lacking consideration of the "metacognition" component, involves only "part-whole" learning. In animal behavior modeling, we designed the integrated maze path as "full path open from the start," allowing rats to perceive the "whole" path initially and continuously make "whole-part" associations during learning to ultimately master the "whole" maze path. In contrast, we designed the progressive maze path as "three path segments gradually opened according to pattern," where rats learn "parts" as path segments are opened over time, ultimately mastering the "whole" maze path.

Furthermore, "learning" is the foundation of "teaching." Marshall (1992) argued that "teaching based on learning" is the primary approach to educational reform and research, and investigating how students learn from their perspective has become the starting point for educational change. We need to focus not only on the external process of "teachers" designing appropriate "teaching methods" but also on the internal process of how "learners" learn. Maze studies with animals have found that males differ from females in spatial navigation strategies and effectiveness (Hawley, Grissom, Barratt, Conrad, & Dohanich, 2012; Keeley, Tyndall, Scott, & Saucier, 2013; Perrot-Sinal, Kostenuik, Ossenkopp, & Kavaliers, 1996; Roof, 1993; Saucier, Shultz, Keller, Cook, & Binsted, 2008), and similar phenomena have been found in human subjects (Munion, Stefanucci, Rovira, Squire, & Hendricks, 2019; Sneider et al., 2015). These studies suggest that gender influences learners' internal learning processes in spatial learning tasks. Since the spontaneous learning process of learners (rats) under integrated learning conditions is the focus of this study, we included the "gender" factor to explore whether rats of different sexes exhibit spontaneous "integration" behavior, thereby understanding the optimal audience characteristics and boundary (support) conditions for integrated learning methods.

Finally, using a 14-unit composite T-maze as the experimental apparatus, we employed a 2 (learning method: integrated vs. progressive) × 2 (sex: male vs. female) between-subjects factorial design to compare maze learning outcomes across four groups of rats. We also designed a series of subsequent experimental tasks to explore the behavioral-level internal mechanisms underlying differences in learning effectiveness.

2 Method

2.1 Subjects

The subjects were 40 one-month-old SD rats (20 males, 20 females), divided into four groups of 10 each: Integrated Learning-Male (IL-Male), Integrated Learning-Female (IL-Female), Progressive Learning-Male (PL-Male), and Progressive Learning-Female (PL-Female). All subjects were randomly assigned to eight housing cages (five per cage) and maintained in a clean animal facility with constant temperature (22.5°C), automated lighting control (lights off at 8:00, on at 20:00), and 24-hour air purification. One week before formal testing, rats received 15 minutes of daily handling interaction. During formal experiments, rats were fed 25g per cage after individual testing to maintain a semi-hungry state; during inter-test intervals, feeding was fixed at 50g per cage to maintain a satiated state. Throughout the experiment, rats' body weight was maintained above 85% of their free-feeding weight. During the learning phase, weight differences between males (89.88±2.04g) and females (89.27±2.04g) were not significant (F(1,36)=0.042, p=0.840, ^{2}=0.00), nor were differences between the integrated group (87.16±2.04g) and progressive group (91.99±2.04g) (F(1,36)=2.83, p=0.100, ^{2}=0.07). In the fourth test task, subject PL-Male-6 died due to low body weight, resulting in missing data for the subsequent three generalization/analysis tasks and four stage fixation tests.

2.3 Experimental Design

The study employed a 2 (learning method: integrated/progressive; IL/PL) × 2 (sex: female/male; Female/Male) between-subjects factorial design. Quantitative measures included number of learning trials, error counts (sum of error detection entries and error entries), travel distance, and completion time. Qualitative measures included characteristic behaviors and path maps. To investigate the effects and internal mechanisms of different learning methods, five test tasks were administered: learning task, one-week retest task, Gestalt (reverse) transfer task, generalization/analysis task, and stage fixation task (Fig. 1c [Figure 1: see original paper]-f). Detailed task descriptions are provided in Appendix

S1.3.

Figure 1 Test task design diagram. Note: a) Basic experimental apparatus, adapted from Tolman (1948). b) The correct path of the basic apparatus was divided into three segments with shape similarity: , , and represent the first, second, and third path segments, respectively, facilitating description of rat behavior characteristics during result reporting. c) Learning and retest task design diagram. The IL group had no segment partitions and was fully open throughout. The PL group was divided into 3 segments using partitions based on maze length and pattern (partitions were placed in grooves for easy insertion/removal). Routes (first path), (first and second paths), and (full path) were the correct paths for PL on days 1-3, 4-7, and 8-12, respectively; route (full path) was also the correct path for IL on days 1-12. During retest, the full path remained open. d) Gestalt (reverse) transfer task design diagram. The food box entrance was sealed with a partition and changed to the starting point; the curtain at the original starting point was moved to the end-point intersection. e) Generalization/analysis task design diagram. In the figure, , , and represent the shortest route, hidden route, and original route, respectively. f) Stage fixation task design diagram. , , and represent the shortest alternative paths for the first, second, and third path segments, respectively, while the original path remained open.

2.4 Experimental Procedure

Figure 2 [Figure 2: see original paper] Research flowchart

(1) **Adaptation phase**: Rats received 15 minutes of daily handling interaction per cage for one week. Adequate food (50g per cage) was provided, and body weight, water intake, and remaining food were recorded. (2) **Formal experiment**: Consisted of 5 tasks. First was a 12-day learning task (one trial per day). Day 1 was limited to 15 minutes for all groups; on days 2-12, rats were removed after finishing eating (within 15 minutes). After one week, a 3-day one-week retest task was administered, followed by a 3-day Gestalt transfer task. After relearning and consolidating the learning-phase path for one day, a 5-day generalization/analysis task was conducted. Following another day of consolidation, a 4-day stage fixation task was administered. All tasks involved removing rats after they finished eating within 15 minutes. (3) **Data collection**: Observation records were completed during testing. The Supersys animal behavior video analysis system (Shanghai Xinruan) was used to analyze experimental videos and export data (including trajectory maps and heat maps). Microsoft Excel, IBM SPSS 18.0, GraphPad Prism 8, and 3D drawing software were used for data analysis and figure preparation. Experimental details are provided in Appendices S1.1 and S1.4.

2.5 Statistical Methods

In statistical analyses, learning method (IL/PL) and sex (Male/Female) were between-subjects variables, while learning trials and path segment (first/second/third path) were within-subjects variables. Dependent variables included error counts, days to learning success, occurrence of specific behaviors, and proportions of specific behaviors. Various combinations of variables were analyzed using ANOVA. Raw data and corresponding analysis tables are provided in Appendix S2.

3 Results

3.1 Learning and Memory Effects

Figure 3 [Figure 3: see original paper] Comparison of learning and memory effects. Note: a) Learning curve: Summary of error counts during the learning phase. “Error count” = “error entry count” + “error detection count,” calculated from the start point to reaching the end-point food box. Error entry count refers to the rat’ s head and center of mass entering an error area (generally passing through a curtain), while error detection count refers to the head entering an error area (generally without passing through the curtain). b) Days to learning success during the learning phase. Days to learning success was defined as the total number of days from the first learning trial until achieving zero errors in the “open path segment.” For the IL group, the “open path segment” was the full maze path, so the total days until zero errors were recorded as days to learning success. For the PL group, the “open path segment” was opened in three stages, so the total days until zero errors in each stage were recorded as days to learning success for that stage. c) Error counts in the one-week retest task. d) Error counts in the Gestalt transfer task. Circle and triangle positions or bar heights in each graph show group means for each trial, with error bars indicating standard error. **p<0.01.

In the learning task (Fig. 3a), the IL group’s learning curve showed an “exponential decline”pattern, while the PL group’s showed a “wave”pattern. A three-factor repeated-measures ANOVA with learning method and sex as between-subjects variables and learning trials as a within-subjects variable revealed significant main effects of learning method, sex, and learning trials, as well as two-way interactions between each pair (see Table 1 in Appendix S2). Regarding days to learning success (Fig. 3b), a two-factor completely randomized ANOVA with learning method and sex as between-subjects variables showed that although main effects (sex: F(1,36)=0.72, p=0.551, ^{2}=0.42, 95%CI=[-2.63, 0.33]; learning method: F(1,36)=3.29, p=0.321, ^{2}=0.77, 95%CI=[-3.93, -0.98]) and interactions (F(1,36)=3.45, p=0.072, ^{2}=0.09, IL and Male: 95%CI=[3.23, 6.18]; PL and Male: 95%CI=[7.03, 9.98]; IL and Female: 95%CI=[5.73, 8.68]; PL and Female: 95%CI=[6.83, 9.78]) were not significant, effect sizes were large. Post-hoc multiple comparisons for learning method showed IL was shorter than PL (F(1,36)=11.36, p=0.002, ^{2}=0.24, 95%CI=[-3.93, -0.98]). Simple effect comparisons of learning method controlling for sex revealed a significant difference between IL-Male and PL-Male groups (t(1,18)=4.12, p=0.000, Cohen' s d=-1.84, r=-0.67, 95%CI[-6.21, -1.40]).

In the one-week retest task (Fig. 3c), a three-factor repeated-measures ANOVA (Table 5) showed no significant differences in error counts between groups (F(1,36)=4.03, p=0.052, ^{2}=0.10, 95%CI=[-0.01, 1.17]).

In the Gestalt transfer task (Fig. 3d), a three-factor repeated-measures ANOVA (Table 6) showed that the IL group made significantly fewer errors than the PL group (F(1,36)=5.50, p=0.025, ^{2}=0.13, 95%CI=[0.28, 3.89]), and males made fewer errors than females (F(1,36)=4.98, p=0.032, ^{2}=0.12, 95%CI=[-3.79, -0.18]).

Figure 4 [Figure 4: see original paper] Comparison of path segments in generalization/analysis and stage fixation tasks. Note: a) Group heat map comparison for the first generalization/analysis test. b) Error count comparison across 5 days of generalization/analysis task. c) Group heat map comparison for the final stage fixation test. d) Proportion comparison of stage fixation by path segment. Brighter areas in heat maps indicate higher exploration density. Circle positions or bar heights in graphs show group means or proportions, with error bars indicating standard error. *$p<0.05$.

In the generalization/analysis task (Fig. 4b), a repeated-measures ANOVA with learning method, sex, and learning trials as factors (Table 7) showed that the IL group made fewer errors across 5 days than the PL group (F(1,35)=4.66, p=0.038, ^{2}=0.12, 95%CI=[-0.99, -0.03]). Examination of group heat maps from the first test (Fig. 4a) revealed that the IL group almost exclusively chose either the original route or the shortest route, while the PL group showed mixed route selection (choosing all three routes), exhibiting a pattern of comprehensive re-searching.

In the final test of the stage fixation task (Fig. 4c-d), all groups consistently chose the original path in the first segment, showed mixed selection (both original and new paths) in the second segment, and consistently chose the new shortest path in the third segment. Coding selection of the original path as 1 and new path as 0, a repeated-measures ANOVA with learning method, sex, and path segment as factors (Table 8) showed no significant main effects of learning method or sex, but a significant main effect of path segment (F(2,70)=40.83, p=0.000, ^{2}=0.54, 95%CI=[-0.07, 0.24]), indicating consistent fixation on the original route in the first path, attempts at new routes in the second path, and preference for new routes in the third path across all groups.

3.2 Behavioral Characteristics of the IL Group During Learning

To further explore the internal characteristics of the IL group during learning, we conducted trajectory analysis of their travel routes (Fig. 5 [Figure 5: see original paper]).

Figure 5 IL group learning process path segment analysis. Note: a) Typical trajectory case examples from the IL group, from left to right: IL-Female-2-1, IL-Female-6-1, IL-Female-9-1. b) and c) Travel distance and time comparisons by path segment for the IL group. Segment time was calculated as "segment path travel time = continuous travel time –start point stationary time." Start point stationary time was subtracted to exclude systematic error from start-point fixation that would artificially inflate first segment time. For distance and time measures, each IL rat's three data units ("first path," "second path," "third path") represent total distance or time across *n* days before "learning success." "Learning success" was defined as completing the full path without errors, which varied by individual. Analyzing only within the range of days to learning success focused the analysis on the learning process from "incompetence to competence" without being influenced by post-learning performance. Circle positions in graphs show group means, with error bars indicating standard error.

As shown in Fig. 5a, IL group trajectory patterns during the learning phase fell into three general categories. The left panel (repeatedly learning the left half before quickly completing the right half) and middle panel (repeatedly learning the first and second paths before quickly completing the third path) appeared on day 1 for IL-Male and days 1-3 for IL-Female groups. The right panel (spontaneous return exploration only in the first path, then quickly completing the second and third paths) was common in IL-Male from day 2 through learning success days and appeared at least once in 9 of 12 days for IL-Female, with 3 IL-Female rats failing to reach the endpoint within 15 minutes during the first three days.

A repeated-measures ANOVA with sex and path segment as factors (Fig. 5b, c; Tables 9 and 10) showed significant main effects of path segment for both distance (F(2,36)=38.01, p=0.000, ^{2}=0.68, first vs. second path: 95%CI=[5.52, 15.63]; first vs. third path: 95%CI=[10.81, 23.45]; second vs. third path: 95%CI=[2.48, 10.63]) and time (F(2,36)=39.10, p=0.000, ^{2}=0.69, first vs. second path: 95%CI=[45.57, 111.60]; first vs. third path: 95%CI=[62.08, 138.43]; second vs. third path: 95%CI=[1.02, 42.33]), showing a gradual decreasing trend. The main effect of sex was significant, with males showing shorter travel distance (F(1,18)=22.51, p=0.000, ^{2}=0.56, 95%CI=[-21.10, -8.15]) and time (F(1,18)=22.10, p=0.000, ^{2}=0.55, 95%CI=[-96.70, -36.97]) than females. Interactions between sex and path segment were significant for both distance (F(2,36)=6.26, p=0.005, ^{2}=0.26) and time (F(2,36)=9.10, p=0.001, ^{2}=0.34).

Overall, IL group travel trajectories showed more intensive learning of the first correct path segment, indicating uneven regional distribution, with this pattern being more pronounced in males than females.

3.3 Behavioral Characteristics of the PL Group During Learning

Figure 6 [Figure 6: see original paper] Exploration density maps of the PL group after new path opening. Note: Group heat maps for PL group on days 4 and 8 of the learning phase. Brighter colors indicate higher exploration density.

To explore PL group behavioral characteristics during learning, we focused on their performance on the first day of new learning stage openings (second and third path openings occurred on days 4 and 8 of the total learning process). As shown in Fig. 6 and Supplementary Figs. 7 [Figure 7: see original paper] and 8 [Figure 8: see original paper], after the second path opened, PL-Male maintained high-density exploration of the first path, while PL-Female engaged in high-density exploration of the newly opened second path. A repeated-measures ANOVA with sex, path segment, and learning trials as factors (Tables 11 and 12) showed an interaction between path segment and sex for travel distance (F(1,18)=5.35, p=0.033, ^{2}=0.23) and a three-way interaction between path segment, learning trials, and sex (F(3,54)=3.13, p=0.033, ^{2}=0.15). No significant sex differences emerged in travel distance or time during the third learning stage (days 8-12) (Tables 13 and 14 ; Supplementary Figs. 9 [Figure 9: see original paper] and 10 [Figure 10: see original paper]).

In summary, after new path segments opened, male and female PL rats explored different path segments intensively: PL-Male focused on the original path, while PL-Female focused on newly opened paths, suggesting that PL-Male emphasized connecting old and new segments while PL-Female treated newly opened segments as entirely new learning material.

3.4 Individual Adaptability During the Learning Phase

To investigate whether the integrated learning method suits each individual, we measured start-point stationary time, whether rats ate at the endpoint, whether they ate chocolate (a more tempting but novel reward stimulus they had not previously encountered), and body weight as indicators of learning method adaptability. A repeated-measures ANOVA with learning method, sex, and learning trials as factors (Fig. 7, Table 15 , Supplementary Figs. 11 [Figure 11: see original paper] and 12 [Figure 12: see original paper]) showed that the IL group ate less at the endpoint (0.51±0.05 vs. 0.78±0.05, F(1,34)=15.93, p=0.000, ^{2}=0.32, 95%CI=[-0.42, -0.14]) and ate less chocolate (0.83±0.03 vs. 0.92±0.03, F(1,36)=4.44, p=0.031, ^{2}=0.12, 95%CI=[-0.16, -0.01]) than the PL group. However, interactions between learning method and sex were not significant for either endpoint eating (F(1,34)=2.92, p=0.097, ^{2}=0.08) or chocolate eating (F(1,36)=4.11, p=0.050, ^{2}=0.10). No significant main effects or interactions were found for body weight or start-point stationary time.

Figure 7 Specific behavioral observation indicators. Note: Proportion refers to the ratio of times a subject ate at the endpoint or ate chocolate during the learning phase out of the total 12 trials. Bar heights show means, with error bars indicating standard error. *$p<0.05$,* **p<0.001.

4 Discussion

4.1 Differences in Learning Effectiveness Between Learning Methods

Overall, the IL group showed better learning outcomes than the PL group in several aspects: (1) The IL group required fewer days to achieve learning success; (2) In the one-week retest task, no significant differences were found between learning methods at the level of correct path memory, but differences re-emerged in the Gestalt (reverse) transfer task, which assessed rats' overall grasp of the maze, indicating that the IL group formed more robust and transferable overall cognitive representations of maze paths; (3) In the generalization/analysis task, the IL group made fewer errors, and heat maps from day 1 showed they more clearly chose the shortest or original routes, whereas the PL group exhibited comprehensive re-exploration behavior, suggesting that, compared to the PL group, the IL group had a clearer grasp of the absolute spatial relationship between start and end points and may have engaged in multi-level categorical processing of remembered routes.

During learning, IL group trajectory maps (Fig. 5) and corresponding indicators showed a decreasing trend in exploration density across the first, second, and third paths. Combined with results from the stage fixation test showing persistent fixation on the first path (original route) across groups, we conclude that the IL group engaged in intensive memory processing of the first path within the overall maze context. Research has shown that the hippocampus can encode spatial memory while also processing "meta-spatial" information that is transferable (Dusek & Eichenbaum, 1997). Modulating hippocampal synaptic plasticity can enhance meta-spatial processing and spatial orientation prediction abilities (Bannerman, Good, Butcher, Ramsay, & Morris, 1995; Saucier & Cain, 1995). Since the correct path shapes of the first, second, and third paths were identical, we speculate that the IL group transferred memory information from the first path when learning the second and third paths. Additionally, in the stage fixation task, all groups chose the shortest path in the second and third paths, suggesting that information learned through transfer may be less solidified and more easily optimized when facing new tasks. The IL group's spontaneous selection of the first path for intensive exploration, followed by relatively rapid completion of the second and third paths, implies they established relationships and connections between different paths and engaged in chunking, representing a potentially "adaptive" learning phenomenon.

However, some individuals in the IL group, particularly during the early learning phase, showed significant anxiety and maladaptation (Fig. 6), as evidenced by less eating at the endpoint and less consumption of chocolate as a novel stimulus (a novelty-suppressed feeding phenomenon; see Bechtholt, Hill, & Lucki, 2007; Dulawa & Hen, 2005; Dulawa, 2009), suggesting they may require additional support.

4.2 Gender Differences

In specific maze learning tasks, males' learning behaviors differed significantly from females' , consistent with previous research showing sex differences in spatial orientation task performance (e.g., Hawley et al., 2012; Keeley et al., 2013; Perrot-Sinal et al., 1996; Roof, 1993; Saucier et al., 2008). Trajectory map and heat map analyses during the learning phase showed that IL-Male exhibited clearer chunking across the three path segments, with more frequent and widespread intensive exploration of the first path. IL-Female appeared more cautious, showing similar regular exploration patterns later than IL-Male, and were more hesitant to eat at the endpoint or consume chocolate after arrival. PL-Male showed similar tendencies, returning to explore the first path at high density after the second path opened and exploring all three paths relatively equally after the third path opened. In contrast, PL-Female explored newly opened paths at high density each time. We therefore speculate that PL-Male similarly tended to establish memory connections between old and new paths based on deep processing of the first path, transferring cognition of the original path to new paths, but this potential was constrained by the artificial stage divisions. PL-Female, however, tended to directly explore unknown new paths.

4.3 Implications for Learning

Although the term "integrated learning" has been proposed by other scholars (陈琦 & 张建伟, 2003; 方华梁, 2018), this study is the first to interpret the concept' s connotation and characteristics through animal behavior modeling, suggesting the natural possibility of the integrated learning concept. Yeager and Walton (2011) emphasized that when using psychological methods to intervene in student learning, attention must be paid to contextual factors. This study implies that educators' understanding of context can be richer and deeper. For example, an integrated learning concept based on students' "whole-part-whole" adaptive process may be more effective for long-term knowledge mastery and transfer, provided that educators offer sufficient initial support based on learners' individual characteristics (e.g., sex, proactive personality; see Zhu, He, & Wang, 2017) and contextual factors such as task nature and environmental support (Walton & Yeager, 2020) to help them through the adaptation period.

5 Conclusion

(1) For rat maze learning, the integrated learning method is more efficient, yielding multi-layered information acquisition with long-term retention and transfer advantages. (2) During the formation of a "cognitive map" of maze paths, memory information exhibits characteristics of wholeness, chunking, categorization, and transferability. (3) In maze learning tasks, male and female rats show distinct learning behavior differences. (4) Some rats exhibit increased anxiety or maladaptation during the initial phase of integrated learning.

References

Bannerman, D. M., Good, M. A., Butcher, S. P., Ramsay, M., & Morris, R. G. M. (1995). Distinct components of spatial learning revealed by prior training and NMDA receptor blockade. *Nature*, *378*(6553), 182-186.

Bechtholt, A. J., Hill, T. E., & Lucki, I. (2007). Anxiolytic effect of serotonin depletion in the novelty-induced hypophagia test. *Psychopharmacology*, *190*(4), 531-540.

陈琦, 张建伟. (2003). 信息时代的整合性学习模型——信息技术整合于教学的生态观诠释. 北京大学教育评论, (03), 90-96.

陈佑清. (2011). 教学论新编. 北京: 人民教育出版社, p226.

Dulawa, S. C., & Hen, R. (2005). Recent advances in animal models of chronic antidepressant effects: The novelty-induced hypophagia test. *Neuroscience & Biobehavioral Reviews*, *29*(4-5), 771-783.

Dulawa, S. C. (2009). Novelty-induced hypophagia. *Neuromethods*, *42*, 247-259.

Dusek, J. A., & Eichenbaum, H. (1997). The hippocampus and memory for orderly stimulus relations. *Proceedings of the National Academy of Sciences of the United States of America*, *94*(13), 7109-7114.

方华梁. (2018). 通识教育课程的整合性学习—对一门名著阅读课程的个案研究. 复旦教育论坛, *16*(02):61+67+62-66.

Hawley, W. R., Grissom, E. M., Barratt, H. E., Conrad, T. S., & Dohanich, G. P. (2012). The effects of biological sex and gonadal hormones on learning strategy in adult rats. *Physiology & Behavior*, *105*(4), 1014-1020.

Keeley R. J., Tyndall A. V., Scott G. A., & Saucier D. M. (2013). Sex difference in cue strategy in a modified version of the Morris water task: Correlations between brain and behaviour. *PLoS One*, 8:e69727.

刘儒德. (2002). 大学生的学习观. 高等教育研究, (04), 77-81.

Marshall, H. H. (1992). *Redefining student learning: Roots of educational change.* Ablex Pub. Corp.

Munion, A. K., Stefanucci, J. K., Rovira, E., Squire, P., & Hendricks, M. (2019). Gender differences in spatial navigation: Characterizing wayfinding behaviors. *Psychonomic Bulletin & Review*, *26*(6), 1933-1940.

Perrot-Sinal, T. S., Kostenuik, M. A., Ossenkopp, K. P., & Kavaliers, M. (1996). Sex differences in performance in the Morris water maze and the effects of initial nonstationary hidden platform training. *Behavioral Neuroscience*, *110*:1309-20.

Roof, R. L. (1993). Neonatal exogenous testosterone modifies sex difference in radial arm and Morris water maze performance in prepubescent and adult rats. *Behavioural Brain Research*, *53*:1-10.

Saucier, D., & Cain, D. P. (1995). Spatial learning without NMDA receptor-dependent long-term potentiation. *Nature*, *378*(6553), 186-189.

Saucier, D. M., Shultz, S. R., Keller, A. J., Cook, C. M., & Binsted, G. (2008). Sex differences in object location memory and spatial navigation in Long-Evans rats. *Animal Cognition*, *11*(1), 129-137.

Skinner, B. F. (1945). The operational analysis of psychological terms. *Psychological Review*, *52*(4), 547-553.

施良方. (2000). 学习论: 学习心理学的原理与理论. 北京: 人民教育出版社.

Schraw, G. (1998). Promoting general metacognitive awareness. *Instructional Science*, *26*(1/2): 113-125.

Sneider, J. T., Hamilton, D. A., Cohengilbert, J. E., Crowley, D. J., Rosso, I. M., & Silveri, M. M. (2015). Sex differences in spatial navigation and perception in human adolescents and emerging adults. *Behavioural Processes*, *111*:42-50.

Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological Review*, *55*(4), 189.

王彦, & 苏彦捷. (2001). 迷宫与动物行为研究. 心理学动态, (03), 73-78.

Walton, G. M., & Yeager, D. S. (2020) Seed and soil: Psychological affordances in contexts help to explain where wise interventions succeed or fail. *Current Directions in Psychological Science*, *29*:3, 219-226.

Yeager, D. S., & Walton, G. M. (2011). Social-psychological interventions in education: they' re not magic. *Review of Educational Research*, *81*(2), 267-301.

张厚粲. (2003). 行为主义心理学. 杭州: 浙江教育出版社.

Zhu, Y., He, W., & Wang, Y. (2017). Challenge-hindrance stress and academic achievement: Proactive personality as moderator. *Social Behavior and Personality*, *45*(3).

朱滢. (2019). 心理学研究中的伦理. 心理学探新, *39*(02), 99-108.

周正怀. (2005a). 桑代克和斯金纳在学习理论上的共通性. 邵阳学院学报, 4(6), 157-159.

周正怀. (2005b). 桑代克和斯金纳在学习理论上的分歧. 湖南第一师范学报, 5(3), 34-37.

Supporting Materials for "Exploring an Animal Behavioral Model of the Integrated Learning Concept"

S1 Research Details

S1.1 Experimental Control Procedures Before formal experiments, experimenters removed rats by cage for 15 minutes of daily handling interaction for one week to help reduce stress and establish secure relationships with the cage environment, cage-mates, and experimenters. Food was controlled at 25g per cage (average 5g per rat, maintaining semi-hungry state) the day before formal testing. During formal experiments, rats were fed 25g per cage after individual testing to ensure semi-hungry state consistency across cages for the next day’ s testing. During inter-test intervals, feeding was fixed at 50g per cage (average 10g per rat, near satiation). Throughout the experiment, rats’ body weight was maintained above 85% of free-feeding weight. For individual rats with slow weight gain or serious weight loss, food was appropriately increased after daily testing, with single-cage feeding to avoid competition, and heating pads (33–40°C) were placed under cages to ensure normal weight gain. During the learning phase, weight differences between males (89.88±2.04g) and females (89.27±2.04g) were not significant (F(1,36)=0.04, p=0.840, ^{2}=0.00), nor were differences between integrated (87.16±2.04g) and progressive groups (91.99±2.04g) (F(1,36)=2.834, p=0.100, ^{2}=0.072). During the experiment, experimenters recorded daily body weight and water intake for each rat. Every 3–4 days, cages were cleaned with alcohol and non-woven fabric, bedding was changed, drinking water (purified via filter) was replaced, and water bottles were washed.

Rats were housed in the Animal Psychology and Behavior Laboratory (EVC environment) at **University, with constant temperature of 22.5°C. A 12:12 light cycle was controlled daily (using timers and blackout curtains to isolate natural light) to maintain normal circadian rhythms (rats are nocturnal, but testing occurred during daytime; the artificial light cycle ensured alertness during testing). Air purifiers regulated indoor air quality, and ceiling-mounted cameras recorded 24-hour laboratory conditions.

S1.2 Experimental Materials

S1.2.1 Daily Animal Care 9 specialized water bottles, 8 medium cages (with feeding and water bottle placement functions on lids, labeled with learning method, sex information, and caretaker contact information), 2 small cages (for temporary housing during bedding changes and for individual feeding of low-weight rats), bedding (wood shavings, corn cobs), rat chow, four-tier storage rack, markers, gram-scale balance, 3 stainless steel containers (2 small, 1 large for weighing rats and food), flatbed cart (for transporting bedding and food), desk lamp with timer, heating pad with temperature controller, yellow medical waste bins, mop, broom, dustpan, and medical waste bags.

S1.2.3 Experimental Apparatus Materials Maze construction materials included: several 4.7mm thick single-sided frosted acrylic panels (250×250mm^2: 31 pieces; 125×250mm^2: 27 pieces; 625×250mm^2: 14 pieces; 510×135mm^2: 1 piece; 500×250mm^2: 1 piece; 130×635mm^2: 14 pieces; 135×260mm^2: 1 piece; 250×10mm^2: 55 pieces), 50mm wide white acrylic seamless joint tape (for sealing maze seams), 500g acrylic adhesive (with syringe), 2 rolls of 45mm wide black strong cloth tape (for assembling the 14-unit composite T-maze), 1.5×1.6m^2

black acrylic fleece fabric (custom-cut into 250×140mm² opaque double-sided strips to control special curtain information for rat memory), 19mm wide small black binder clips (for securing maze curtains), 0.3mm thick galvanized wire (for hanging maze curtains), and 3×3m² dark gray floor mats.

Note: The basic experimental apparatus included curtains, partitions, and food boxes (with a rectangular black ceramic bowl at the left end of the food box), used in all five experimental phases.

Supplementary Figure 1 Integrated maze apparatus design diagram

S1.2.4 Cleaning and Protection Experimenter supplies: disposable caps, shoe covers, masks, gloves, lab coats; alcohol hand sanitizer, iodine, cotton balls, swabs, tweezers, and other first aid supplies for scratches.

Subject supplies: non-woven fabric (also called dusting paper), 75% alcohol spray (for odor removal).

S1.2.5 Other Hardware and Software Materials Conventional animal housing equipment (EVC level), delayed power supply equipment (emergency backup), HikVision DVR monitoring equipment (4-channel DS-7104N-F1/4P), HikVision cameras (DS-IPC-T12-I/POE), compatible USB drives, mobile hard drives, desk lamps with timers, heating pads with temperature controllers, etc.

Software included Format Factory, Camtasia 9 (TechSmith), Supermaze animal behavior video analysis system (Shanghai Xinruan), GraphPad Prism 8, Microsoft Excel 2017, SPSS 18.0, and 3D drawing software.

S1.3 Experimental Paradigm Design The integrated learning animal behavior maze design consisted of 5 modules. The maze outline was standard size, with partition and slot designs and curtain production customized for integrated learning research needs.

During the learning phase, the progressive group’ s partitions divided the maze into 3 segments based on path length (equal length across three segments) and pattern transfer characteristics (similar shapes across three segments). The integrated group had full path access. The experimental apparatus was designed according to operational definitions of integrated and progressive learning methods (see Supplementary Fig. 2). The one-week retest task assessed rats’ long-term memory of maze paths to examine differences in memory robustness between learning methods (see Supplementary Fig. 2). The Gestalt transfer task tested rats’ “holistic” memory of correct maze paths to examine connections between path segment memories (Supplementary Fig. 3). The generalization/analysis test assessed rats’ absolute spatial orientation cognition to examine processing depth and levels of path segments (Supplementary Fig. 4). The stage fixation test examined whether progressive group rats developed relative spatial orientation advantages from segment cues and revealed how rats used and applied transferable information between path segments (Supplementary Fig. 5).

Supplementary Figure 2 Maze design for learning and retest phases. Note: Red partitions were used only for the progressive group during the learning phase (partitions placed in grooves for easy insertion/removal). Yellow, red, and green routes were the correct paths for PL on days 1-3, 4-7, and 8-12, respectively; the green route was also the correct path for IL. During retest, partitions were removed for both groups.

Supplementary Figure 3 Maze design for Gestalt transfer task. Note: The "food box" entrance was sealed with a partition and changed to the "start point"; the curtain at the original start point was moved to the "end point" intersection.

Supplementary Figure 4 Maze design for generalization/analysis test. Note: Yellow, red, and green represent the shortest route, original route, and hidden route (partition removed behind curtain in error area), respectively, used for days 1-5 of generalization/analysis testing.

Supplementary Figure 5 Maze design for stage fixation test. Note: Yellow, green, and blue represent the shortest paths for the first, second, and third path segments, respectively, used for days 1-4 of stage fixation testing while original paths remained open.

S1.4 Research Procedure

(1) Design and construct a properly sized 14-unit composite T-maze. (2) Conduct pilot experiments with 12 rats to establish experimental procedures, observation record forms, quantitative analysis indicators, experimental operation essentials, and conditions for excluding systematic interference. (3) Purchase 40 one-month-old rats, house them in cages, and conduct 7 days of daily 15-minute handling interaction before formal experiments. Provide adequate food (50g per cage), recording body weight, water intake, and remaining food as references for formal experimental feeding amounts. (4) Conduct formal experiments in cage order: Integrated-Male 1, Progressive-Male 1, Integrated-Female 1, Progressive-Female 2, Integrated-Male 2, Progressive-Male 2, Integrated-Female 2, Progressive-Female 2. Feed each cage 25g after testing to ensure consistent semi-hungry levels across cages for the next day' s testing period. (5) Before formal experiments, place a square black ceramic bowl with food at the endpoint (rats preferred milk chocolate chips, but since they had not previously consumed chocolate, the bowl initially contained 1 small pellet of regular chow and 1 chocolate chip. Once all rats began eating chocolate chips, only 1 chocolate chip was placed. The ceramic bowl provided some cue function, indicating food location changes and preventing reinforcement loss from forgetting to place food, as the bowl itself served as a reinforcer). Before testing, rats were weighed and placed at the start point with an extended arm while the experimenter stood back to avoid blocking the camera and preventing valid initial data collection. During testing, experimenters manually recorded special behaviors such as whether rats

ate at the endpoint or consumed chocolate. (6) After testing, maze walls were sprayed with alcohol and wiped with non-woven fabric as needed. Curtains were adjusted to avoid odor (feces, urine, hair) from previous rats and changes in curtain drape patterns affecting subsequent rats. (7) Original videos were backed up daily, cropped into analyzable standard formats, and stored on mobile hard drives. (8) The learning phase lasted 12 days. For the progressive group, a partition was placed at the end of the first segment on days 1-3 for 3 days of learning; on days 4-7, the first partition was removed and a partition placed at the end of the second segment for 4 days of learning; on days 8-12, the second partition was removed for 5 days of learning. The integrated group had no partitions for all 12 days. On day 1 of the learning phase, each rat was timed for 15 minutes (ensuring most rats exhibited adapted exploration and obtained food, and balancing the possibility that PL rats might reach the endpoint too quickly due to short path segments). On days 2-12, rats were removed after reaching the endpoint and finishing food (waiting for them to finish before removal to avoid affecting motivation). (9) Testing was suspended for 1 week, with each cage receiving 50g daily food and body weight and water intake recorded. During this period, 12 days of learning phase videos were processed. Videos were batch-analyzed in the Supersys system. Although day 1 involved 15 minutes of exploration per rat, the trigger automatically cropped video data until first endpoint arrival for analysis. In the one-week retest phase, both integrated and progressive groups completed identical full-path maze tests. (10) For Gestalt transfer testing, the food box opening was sealed with a partition, start and end points were swapped, the curtain before the endpoint was moved to before the start point, and the food dish was placed at the new endpoint (original start point) for 3 days of testing. (11) After relearning the learning-phase path for one day (to reduce reverse transfer test effects on generalization/analysis testing), a 5-day generalization/analysis test was conducted. (12) After another day of consolidation (to reduce generalization/analysis test effects on stage fixation testing), a 4-day stage fixation test was administered. (13) Batch analysis was performed using the Supersys system. Trajectory maps were reviewed in Supersys, and some incomplete or redundant video segments were re-backed-up and cropped to ensure data quality. Data were organized using Excel and SPSS 18.0, and analyzed and graphed using GraphPad Prism 8.

S1.5 Detailed Data Processing Steps First, 1,113 trials (with missing data for the last three generalization/analysis tasks and all four stage fixation tests for “PL-Male-6”) were video-recorded and cached using ceiling-mounted camera monitoring equipment. Valid video segments were exported in AVI format. Next, Format Factory and TechSmith Camtasia Studio 9 were used to crop and format original videos into 640×480 screen size, Xvid format, single-rat videos with irrelevant information removed.

Supplementary Figure 6 Experimental design-area settings in Supermaze animal behavior video analysis system

Then, the *Supermaze Animal Behavior Video Analysis System* (Shanghai Xinruan Information Technology Co., Ltd.) was used to create an analysis platform (see Fig. 6). Settings included: dynamic background algorithm, 3-point tracking (head, center of mass, tail), rat brightness vs. background brightness contrast set to "brighter," working mode set to "erode then dilate" (parameter: 2 pixels, primarily for eliminating small objects, separating objects at thin points, smoothing boundaries of larger objects), area threshold enabled for head and center of mass judgment (only recorded when both head and center of mass entered designated area), head exploration time threshold set to 5×100ms, test parameter delay end set to 900s, trigger set to "first entry into Foodbox area (set as Foodbox for integrated group; for progressive group set as First period End on days 1-3, Second period End on days 4-7, and Foodbox on days 8-12) with 1s stay." After setting, the "batch processing video" function in "collection analysis" was used to dynamically analyze 1,113 videos. After analysis, raw data were exported in "data management." Finally, trajectory maps in the Supermaze analysis system were reviewed, and some incomplete or redundant video segments were re-backed-up and cropped to ensure data quality. Data were organized using Excel and SPSS 18.0, and analyzed and graphed using GraphPad Prism 8.

S2 Experimental Results Statistical Tables and Supplementary Figures

Raw research data have been uploaded to Baidu Cloud for access.
Link: https://pan.baidu.com/s/1ghol7fjVvDBkL2LTR0BqLg
Extraction code: otrn

Supplementary Table 1 Three-factor repeated-measures ANOVA for error counts in learning phase

Effect	F (DFn, DFd)
Learning trials	F(11, 396) = 29.42***
Learning method	F(1, 36) = 15.54***
Sex	F(1, 36) = 11.55**
Learning trials × Learning method	F(11, 396) = 27.99***
Learning trials × Sex	F(11, 396) = 2.45**
Learning method × Sex	F(1, 36) = 8.67**
Learning trials × Learning method × Sex	F(11, 396) = 1.82*

Note: *p<0.05,* ***p<0.01,*** p<0.001.

Supplementary Table 2 Two-factor completely randomized ANOVA for days to learning success

Effect	F (DFn, DFd)
Sex	F(1, 36) = 0.73
Learning method	F(1, 36) = 3.29
Sex × Learning method	F(1, 36) = 3.45

Supplementary Table 3 Post-hoc multiple comparisons for days to learning success

Comparison	F (DFn, DFd)
Male vs. Female	F(1, 36) = 2.50
IL vs. PL	F(1, 36) = 11.36**

Note: **p<0.01.

Supplementary Table 4 Simple effect comparisons of learning method at each sex level

Comparison	t (df)	Cohen’ s d	r	95% CI
IL-Male vs. PL-Male	4.12*** (1,18)	-1.84	-0.67	[-6.21, -1.40]

Note: ***p<0.001.

Supplementary Table 5 Three-factor repeated-measures ANOVA for error counts in one-week retest task

Effect	F (DFn, DFd)
Learning trials	F(2, 72) = 2.19
Learning method	F(1, 36) = 4.03
Sex	F(1, 36) = 1.19
Learning trials × Learning method	F(2, 72) = 1.73
Learning trials × Sex	F(2, 72) = 0.30
Learning method × Sex	F(1, 36) = 0.00
Learning trials × Learning method × Sex	F(2, 72) = 0.30

Supplementary Table 6 Three-factor repeated-measures ANOVA for error counts in Gestalt transfer task

Effect	F (DFn, DFd)
Learning trials	F(2, 72) = 25.64***

Effect	F (DFn, DFd)
Learning method	F(1, 36) = 5.50*
Sex	F(1, 36) = 4.99*
Learning trials × Learning method	F(2, 72) = 0.04
Learning trials × Sex	F(2, 72) = 0.52
Learning method × Sex	F(1, 36) = 0.10
Learning trials × Learning method × Sex	F(2, 72) = 0.12

Note: *$p<0.05$,* **$p<0.001$.

Supplementary Table 7 Three-factor repeated-measures ANOVA for 5-day generalization/analysis task

Effect	F (DFn, DFd)
Test trials	F(4, 140) = 3.00*
Learning method	F(1, 35) = 4.66*
Sex	F(1, 35) = 1.32
Test trials × Learning method	F(4, 140) = 1.11
Test trials × Sex	F(4, 140) = 0.27
Learning method × Sex	F(1, 35) = 1.53
Test trials × Learning method × Sex	F(4, 140) = 0.84

Note: *$p<0.05$.

Supplementary Table 8 Three-factor repeated-measures ANOVA for proportion of rats still choosing original route in final stage fixation test

Effect	F (DFn, DFd)
Path segment	F(2, 70) = 40.83***
Learning method	F(1, 35) = 1.18
Sex	F(1, 35) = 0.42
Path segment × Learning method	F(2, 70) = 2.32
Path segment × Sex	F(2, 70) = 1.22
Learning method × Sex	F(1, 35) = 0.05
Path segment × Learning method × Sex	F(2, 70) = 1.50

Note: ***$p<0.001$.

Supplementary Table 9 Two-factor repeated-measures ANOVA for travel distance by path segment in IL group

Effect	F (DFn, DFd)
Path segment	F(2, 36) = 38.01***
Sex	F(1, 18) = 22.51***
Path segment × Sex	F(2, 36) = 6.26**

Note: **$p<0.01$,** *$p<0.001$.

Supplementary Table 10 Two-factor repeated-measures ANOVA for travel time by path segment in IL group

Effect	F (DFn, DFd)
Path segment	F(2, 36) = 39.10***
Sex	F(1, 18) = 22.10***
Path segment × Sex	F(2, 36) = 9.10**

Note: **$p<0.01$,** *$p<0.001$.

Supplementary Table 11 Three-factor repeated-measures ANOVA for distance in PL group phase 2

Effect	F (DFn, DFd)
Path segment	F(1, 18) = 0.70
Learning trials	F(3, 54) = 7.07***
Sex	F(1, 18) = 0.00
Path segment × Sex	F(1, 18) = 5.35*
Learning trials × Sex	F(3, 54) = 2.18
Path segment × Learning trials	F(3, 54) = 2.00
Path segment × Learning trials × Sex	F(3, 54) = 3.13*

Note: **$p<0.01$,** *$p<0.001$.

Supplementary Table 12 Three-factor repeated-measures ANOVA for time in PL group phase 2

Effect	F (DFn, DFd)
Path segment	F(1, 18) = 0.13
Learning trials	F(3, 54) = 8.00***
Sex	F(1, 18) = 0.30
Path segment × Sex	F(1, 18) = 4.14
Learning trials × Sex	F(3, 54) = 0.85
Path segment × Learning trials	F(3, 54) = 0.92

Note: ***p<0.001.

Supplementary Table 13 Three-factor repeated-measures ANOVA for distance in PL group phase 3

Effect	F (DFn, DFd)
Path segment	F(2, 36) = 15.86***
Learning trials	F(4, 72) = 5.53**
Sex	F(1, 18) = 0.43
Path segment × Sex	F(2, 36) = 2.57
Learning trials × Sex	F(4, 72) = 0.64
Path segment × Learning trials	F(8, 144) = 2.33*
Path segment × Learning trials × Sex	F(8, 144) = 0.31

Note: *p<0.05,* ***p<0.01,*** p<0.001.

Supplementary Table 14 Three-factor repeated-measures ANOVA for time in PL group phase 3

Effect	F (DFn, DFd)
Path segment	F(2, 36) = 30.87***
Learning trials	F(4, 72) = 12.86***
Sex	F(1, 18) = 0.46
Path segment × Sex	F(2, 36) = 2.42
Learning trials × Sex	F(4, 72) = 0.41
Path segment × Learning trials	F(8, 144) = 10.84***
Path segment × Learning trials × Sex	F(8, 144) = 1.15

Note: ***p<0.001.

Supplementary Table 15 Between-subjects results from three-factor repeated-measures ANOVA on learning method adaptability during learning phase

Effect	F (DFn, DFd)
Body weight	F(1, 36) = 2.80
Start-point stationary time	F(1, 36) = 0.04
Eat at endpoint	F(1, 34) = 15.93***
Eat chocolate	F(1, 36) = 4.44*
Learning method × Sex (body weight)	F(1, 36) = 1.39
Learning method × Sex (start time)	F(1, 36) = 0.64
Learning method × Sex (eat endpoint)	F(1, 34) = 2.92
Learning method × Sex (eat chocolate)	F(1, 36) = 4.11

Note: The three factors were learning method, sex, and learning trials. Changes in proportions of endpoint eating or chocolate eating across learning trials are shown in Supplementary Figs. 11 & 12. Raw data for endpoint eating were from learning trials 2-12 because trial 1 was limited to 15 minutes of exploration without recording endpoint eating behavior; other indicators were from trials 1-12. Each indicator represents total proportion or mean across the learning phase. *p<0.05,* **p<0.001.

Supplementary Figure 7 Sex comparison of travel time for first and second paths in PL group on days 4-7

Supplementary Figure 8 [Figure 8: see original paper] Sex comparison of travel distance for first and second paths in PL group on days 4-7

Supplementary Figure 9 Sex comparison of travel time for first, second, and third paths in PL group on days 8-12

Supplementary Figure 10 [FIGplementary Figure 10] Sex comparison of travel distance for first, second, and third paths in PL group on days 8-12

Supplementary Figure 11 Changes in proportion of endpoint eating across learning trials for each group

Supplementary Figure 12 [Figure 12: see original paper] Changes in proportion of chocolate eating across learning trials for each group

S3 Sample Experimental Videos

Seven representative experimental videos from the study are available for download:

Link: https://pan.baidu.com/s/1m_5zCjnJf5LT4NDtwI_7GA
Extraction code: mbx5

Video 1: Example of learning task completion (IL-Male-2, learning task day 12)
Description: On day 12 of the learning task (final day), most subjects completed the maze with zero errors, while a few made 1-4 errors, with significant group differences in error distribution (F=5.128, p=0.03). All IL-Male subjects made zero errors; IL-Female had 1 rat with 4 errors and the rest zero; PL-Male had 3 rats with 1 error, 1 rat with 3 errors, and the rest zero; PL-Female had 4 rats with 1 error, 1 rat with 2 errors, 2 rats with 3 errors, and the rest zero.

Video 2: Example of Gestalt transfer task completion (IL-Male-1, Gestalt transfer task day 3)
Description: On day 3 of the Gestalt transfer task (final day), most subjects completed the task with few or zero errors, while a few made many errors, with significant group differences (Table 5). IL-Male had 5 rats with 1 error and the rest zero; IL-Female had 3 rats with 1 error, 1 rat with 2 errors, 1 rat with 4 errors, 1 rat with 3 errors, 1 rat with 4 errors, and the rest zero; PL-Female had

1 rat with 1 error, 1 rat with 2 errors, 1 rat with 3 errors, 2 rats with 6 errors, 1 rat with 7 errors, 1 rat with 8 errors, 1 rat with 11 errors, and the rest zero.

Video 3: Example of IL group focusing on first path during learning (IL-Male-5, learning phase day 2)
Description: IL-Male-5 made multiple return explorations in the first path but passed through the second and third paths with few errors. Maze path segmentation is shown below. Data results are presented in Fig. 5 of the main text.

Note: The correct path of the basic apparatus was divided into three segments with shape similarity: red, green, and blue represent the first, second, and third paths, respectively.

Video 4: Example of PL-Male focusing on old path after new segment opening (PL-Male-9, learning phase day 4)
Video 5: Example of PL-Female focusing on new path after new segment opening (PL-Female-9, learning phase day 4)
Description for Videos 4 & 5: After new path segments opened, PL-Male returned at the end of the original segment to re-explore the first path before entering the second path to reach the endpoint. PL-Female directly entered the second path and then made return explorations within it before reaching the endpoint. Schematic of PL three-stage opening is shown below. Data results are presented in Fig. 6 of the main text.

Note: Red partitions were used only for PL during the learning phase. Yellow, red, and green routes were the correct paths for PL on days 1-3, 4-7, and 8-12, respectively. PL used partitions to divide the maze into 3 segments based on length and pattern (partitions placed in grooves for easy insertion/removal).

Video 6: Rapid presentation of all trajectory maps for 5 tests in generalization/analysis task
Description: We recorded the export process of all subjects' trajectory maps for the 5 generalization/analysis tests using screen recording software, with continuous playback separated by group. Playback order: IL then PL; male then female; cycling in order of individual rats 1-5 days (40 subjects total). The lower-left label "IL-Male1-1" indicates "Integrated-Male group rat 1, first generalization/analysis test." Pattern: IL group mostly chose shortest or original routes; PL group mostly showed comprehensive searching without clear patterns. Generalization/analysis task schematic is shown below. Data results are presented in Figs. 4a and 4b of the main text.

Note: In the generalization/analysis task, yellow, red, and green represent the shortest route, original route, and hidden route (partition removed behind curtain in error area), respectively, used for days 1-5 of testing.

Video 7: Example of subject showing inertial fixation on first original path in stage fixation test (IL-Male-10, fourth test)
Description: In the fourth test of the stage fixation task, all groups consistently

chose the original route in the first path, while more chose the shorter route in the other two paths. Stage fixation task schematic is shown below. Data results are presented in Figs. 4c and 4d of the main text.

Note: In the stage fixation task, yellow, green, and blue represent the shortest paths for the first, second, and third path segments, respectively, while original paths remained open.

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv —Machine translation. Verify with original.