Original Article
ISSN (Online): 2582-7472

ShodhKosh: Journal of Visual and Performing Arts
January-June 2026 7(1), 599–612

VISUAL LANDSCAPE OPTIMIZATION DESIGN GUIDELINES FOR ULTRA-LONG HIGHWAY TUNNELS: BALANCE BETWEEN SAFETY AND EXPERIENCE

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Received 28 March 2026
Accepted 29 April 2026
Published 07 May 2026

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DOI
10.29121/shodhkosh.v7.i1.2026.7867

Funding: This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

ABSTRACT

With the rapid expansion of China's expressway network, significant progress has been made in the construction of ultra-long tunnels (>3,000 meters in length). However, the enclosed and monotonous visual environment within these tunnels also poses safety risks such as driver fatigue, decreased attention, and increased accident rates. Traditional tunnel landscape design often faces a dilemma: oversimplification can easily cause visual fatigue, while excessive decoration can easily distract attention. There is a lack of scientifically quantified standards to achieve a balance between visual stimulation and driver safety. Therefore, this study proposes guidelines for optimizing visual landscape design that balances safety and driving experience. Based on Gestalt psychology, this study constructs a visual element quantification model centered on perceptual organization principles (such as proximity and similarity) to replace traditional physical component classification methods. Through a tunnel landscape image evaluation experiment, 40 drivers were invited to rate 50 tunnel images on the basis of attention and comfort, generating a total of 4,000 data points for analysis. Key findings indicate that the number of visual elements significantly influences driver attention and emotional state. The optimal range is 4–5 elements, which best maintains concentration and driving comfort. Too few (1–3) can lead to an "information desert," increasing cognitive load and fatigue. Too many (6–9 or more) can easily cause distraction and anxiety. This study focuses on shifting tunnel landscape design from a single-engineering safety focus to a balanced emphasis on human factors and safety, providing a scientifically quantified basis and implementation path for the landscape design of the super-long tunnels on the Nujiang Expressway.

Keywords: Ultra-Long Highway Tunnel, Landscape Design, Driving Safety, Driving Experience

1. INTRODUCTION

With the sustained and rapid development of the national economy, China has made remarkable achievements in the field of highway tunnel construction, and has achieved a historic leap in both scale and technical level. In particular, since the beginning of the 21st century, with an average annual growth rate of 20%. As of 2022, there are 24,850 highway tunnels in China, and 1,599 super-long highway tunnels have been built (L>3,000 m is a super-long tunnel), with a total length of 7,170.8 kilometers, constantly breaking world records.

However, the rapid expansion of the tunnel network, showing a trend of larger diameter, higher speed limit, and longer length, is also accompanied by safety challenges that cannot be ignored. Studies have shown that compared with ordinary highway sections, the incidence of traffic accidents in high-speed super-long tunnels is significantly higher, posing a prominent traffic safety hazard. For high-speed super-long tunnels, their inherent spatial closure and visual monotony can easily cause drivers to feel deeply fatigued and distracted, which in turn causes accidents, making the research on safe landscape design for such tunnels particularly urgent and important. The current practice of tunnel landscape design often falls into a dilemma: on the one hand, the overly simple or even "no landscape" design makes the driver exposed to a highly monotonous and closed environment lacking visual stimulation for a long time, which is very likely to induce visual fatigue and psychological fatigue, posing a potential threat to driving safety; on the other hand, excessive decoration or the introduction of overly complex and dynamic landscape elements (such as dense greenery and dazzling lights) may unnecessarily distract the driver's attention and increase the risk of accidents. The core of this dilemma lies in the lack of scientific and quantitative design standards to guide how to achieve the best balance between relieving visual fatigue and avoiding distraction.

Reasonable and moderate landscape design intervention can effectively relieve the driver's visual fatigue, improve the spatial perception and environmental comfort inside the tunnel, thereby significantly reducing the probability of traffic accidents while improving the driving experience.

2. RESEARCH OBJECTIVES

This research aims to formulate landscape design guidelines for the super-long tunnel on Nujiang Expressway that take into account both safety and driving experience.

3. LITERATURE REVIEW

3.1. CORE SAFETY ISSUES OF TUNNEL DRIVING

3.1.1. LIMITED VISUAL FIELD AND NARROWED ATTENTION SPAN

The closed structure of the tunnel causes the driver's field of vision to be drastically reduced, and the driver's attention is forced to focus on the narrow area ahead. This limited field of vision not only limits the driver's ability to perceive the surrounding environment, but also makes it difficult for him to obtain enough reference objects to predict potential dangerous situations. Studies have shown that when the driver's field of vision is limited, his ability to predict will be significantly reduced, and the reaction time to emergencies will be prolonged. Due to the complex lighting conditions inside the tunnel, the driver may experience a rapid change from bright to dim when entering the tunnel. This sudden change in the light environment will cause a short-term "visual blind spot", further exacerbating the driving risk.

3.1.2. GEOMETRIC CLOSURE AND INCREASED COGNITIVE LOAD

The geometric enclosure of the tunnel not only brings a sense of physical oppression, but also significantly increases the cognitive load of the driver. The physical existence of the tunnel wall will cause psychological pressure on the driver, especially during long driving, this pressure will gradually accumulate, leading to increased anxiety and fatigue of the driver. The reflection of sound waves in the tunnel will also aggravate auditory irritation, because the roar of the engine is repeatedly reflected in the closed space, forming a continuous noise, which not only affects the driver's attention, but also may induce his anxiety.

3.1.3. MONOTONY BOREDOM AND LOW AROUSAL

The monotony of tunnel driving sections is one of the important factors that lead to driver fatigue and decreased attention. In an environment lacking visual changes for a long time, the driver's brain activity will gradually decrease, entering a state of "autopilot", and the ability to respond to potential risks will also be weakened. Studies have shown that this monotonous visual input will lead to an increase in the proportion of alpha waves (relaxed state) in the brain wave, thereby lowering the driver's alertness threshold and making him slow to react when encountering emergencies.

3.2. RISK CHARACTERISTICS AND MECHANISMS OF TUNNEL ZONING

3.2.1. ENTRANCE SECTION: HIGH LOAD DANGER ZONE

The entrance section of a tunnel is one of the most dangerous areas during driving. The core cause is the drastic change in the light environment. When the driver enters the tunnel from the high-brightness external environment, the pupil needs time to adjust to the low-brightness environment inside the tunnel. This process usually takes 3-10 seconds, so during this short period of time, the driver may experience a short "visual blind spot". This visual adaptation disorder not only affects the driver's visual perception ability, but also causes the brain to process the residual image of strong light and new information in the dark environment at the same time, thereby causing instantaneous cognitive overload.

The chain reaction includes: (1) Visual adaptation disorder, the contrast between light and dark exceeds the adjustment ability of the human eye (usually >100:1), making it difficult for the driver to see the road and surrounding environment clearly. (2) Instantaneous cognitive overload, the brain needs to process the residual image of strong light and new information in the dark environment at the same time, increasing the cognitive burden. (3) Stress response, increased heart rate, muscle tension, and increased instinctive braking or steering operations, increasing the risk of accidents. Abnormally high arousal, excessive alertness consumes psychological resources and induces subsequent fatigue.

In terms of superimposed risks, the entrance to a tunnel is often accompanied by speed fluctuations (deceleration adaptation) and lane convergence (narrowing of the road width), which further amplifies the probability of accidents. For example, when entering a tunnel, a driver may slow down due to changes in light, while other vehicles may still be driving at high speed, increasing the risk of collision.

3.2.2. DRIVING SECTION: LOW WAKE-UP DANGER ZONE

The design of the middle section of the tunnel is guided by "traffic efficiency", but the extremely simplified environment violates the needs of human senses. This design causes drivers to face continuous geometric closure and sound wave reflection problems during driving, further exacerbating their psychological and physiological pressure.

The risk evolution path includes: (1) The continuous pressure of geometric closure, the sense of approach of the side wall inhibits the driver's spatial perception ability, making it difficult for him to accurately judge the surrounding environment. Sound wave reflection is enhanced, the reverberation time is extended to 2-4 seconds (about 0.5 seconds on open roads), and the noise annoyance index increases by more than 30%, resulting in increased anxiety and fatigue of drivers. (2) Anxiety and fatigue accumulate, cortisol levels increase, decision-making ability decreases, and drivers react slowly when faced with emergencies. (3) The arousal level continues to decline, and the monotonous visual input leads to an increase in the proportion of alpha waves (relaxed state) in the brain wave, and a decrease in the alert threshold, which makes the driver's reaction delay reach more than 1.5 seconds when encountering emergencies.

3.2.3. EXIT ZONE: PERCEPTION DISTORTION DANGER ZONE

1) The "white hole effect" causes visual collapse. When the low illumination in the tunnel is suddenly exposed to the strong light environment outside, the cone cells of the retina are instantly saturated, resulting in a 3-5 second light spot blind zone in the central field of vision (equivalent to 66-110 meters of blind driving at a speed of 80 km/h).
2) Speed illusion leads to behavioral loss of control. The closed environment in the tunnel blunts the speed perception, making the subjective feeling only 60 km/h when the actual speed is 80 km/h. At the moment of exiting, the field of vision suddenly widens (the horizontal angle of view expands from 40° to 120°), and the accelerated visual flow field strengthens the speed underestimation effect, inducing instinctive acceleration behavior, and the braking reaction delay reaches 1.2 seconds;
3) Spatial orientation obstacles amplify the trajectory deviation, strong light obscures the distant road signs, superimposed on the exit curve line shape visibility (curvature misjudgment rate ±15%) and sudden weather

interference (the trajectory deviation increases by 70% in rainy and foggy days). Multiple factors work together to increase the risk of vehicle lateral displacement exceeding the standard by 400%. Secondary collisions account for up to 35% of accidents in this section, forming a typical chain reaction of "out of control upon exiting".

In terms of accident mechanism, the low arousal state causes the driver to ignore minor risks (such as the deceleration of the vehicle in front), and the reaction delay can reach more than 1.5 seconds in case of emergencies, which significantly increases the probability of traffic accidents. Therefore, the design of the tunnel driving section needs to comprehensively consider the physiological and psychological needs of the driver, and improve the driver's attention and alertness by optimizing lighting, increasing visual stimulation, etc., so as to reduce the risk of accidents.

Figure 1

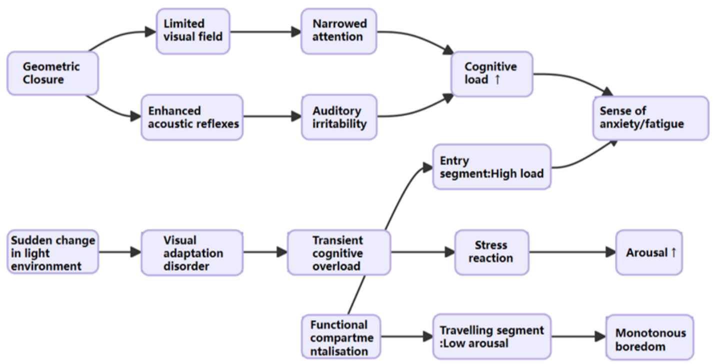


Figure 1 The Relationship Between Tunnel Space and Emotions

Source: Author

4. LIMITATIONS OF TRADITIONAL LANDSCAPE ELEMENT CLASSIFICATION

Existing research on tunnel landscapes mostly focuses on the functional design of physical components (such as lighting and wall structure) or aesthetic classification (such as color and material), but lacks systematic quantification of drivers' dynamic visual cognition. For example: (1) The structure-oriented classification method divides landscape elements into physical components such as ceiling, side wall, road surface, and landscape belt according to spatial position, but does not consider the driver's visual integration mechanism; (2) The functional attribute classification method divides elements into independent variables such as lighting, color, and guide signs, resulting in element fragmentation analysis and ignoring the integrity of visual cognition.

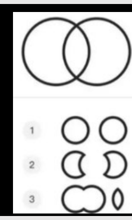
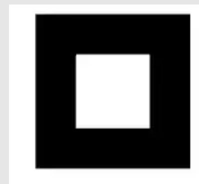
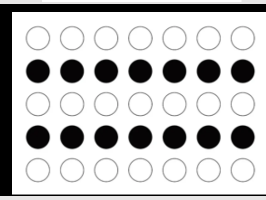
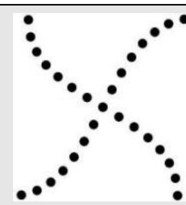
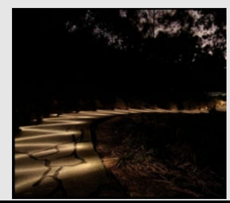
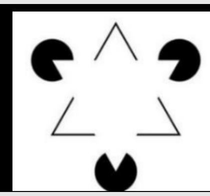
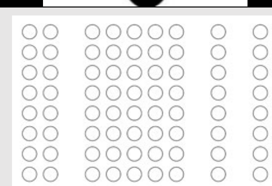
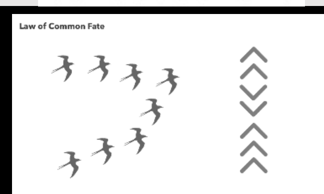
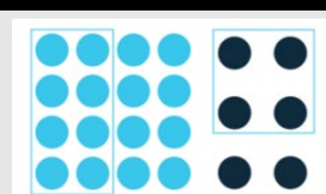
Quantitative bottleneck. Existing methods are difficult to explain the phenomenon that "starry sky ceiling" is regarded as a single element while "double pattern ceiling" is regarded as a double element. The core contradiction lies in not distinguishing the difference between physical entities and visual perception units.

5. APPLICATION OF GESTALT PRINCIPLES OF ORGANIZATION

Only by viewing things as organized and structured wholes can we fully analyze things; on the contrary, if we break them down into raw perceptual elements, we will not be able to fully understand them (specifically referring to psychological phenomena here). The principle of organization is to intuitively group or integrate fragmented information. For example: when we see a house, we usually don't intuitively see the house as bricks, glass, wood boards, etc., but as a complete house. These German psychologists are called Gestalt psychologists, and Max Wertheimer, one of the founders of Gestalt psychology, and his descendants proposed some perceptual organization principles Table 1 and their embodiment in environmental space design. The principle of simplicity can be regarded as the default strategy for perceptual organization. The brain always tends to choose the simplest and most regular way to organize perceptual information, so as to quickly understand complex things.

Table 1

Table 1 Gestalt Psychology Organizational Principles

Organizational Principles	Illustrate	Legend	Picture
Simplicity	Humans tend to organize complex sensory stimuli into simple, regular wholes, which helps us understand the efficiency and mechanism of the brain in processing information.		
Subject-Background	Revealing how important subjects and background are distinguished during perception lays foundation for study of visual selectivity and priority.		
Similarity	All other things being equal, when there are multiple stimuli in perceptual field, observers will tend to group together those elements that have the most similar appearance. (The human eye tends to associate similar elements in a composition.)		
Continuity	Since human vision prefers smooth and continuous objects, it perceives sensory stimuli as continuous and connected objects.		
Closure	Observers tend to interpret stimuli as complete units rather than a collection of fragments. Therefore, when the boundaries of a figure are obscured, human perception will automatically fill in the missing parts to make the figure a complete whole.		
Proximity	All other things being equal, observers tend to group spatially adjacent objects or graphic elements into a perceptual unit.		
Common destiny	All other things being equal, observers tend to group together objects that behave similarly (moving at similar speeds, in the same direction).		
Regional	Treat objects bounded by the same boundary as complete objects		

Source: Author

In tunnel landscape design, the quantification of landscape elements involves not only the identification of visual elements, but also their weight and influence in visual perception. Gestalt psychology emphasizes that the human visual system has a tendency to organize complex inputs into holistic perceptual units, rather than processing single elements in isolation. In tunnel driving scenarios, this mechanism is reflected in the driver's grouped perception of visual elements, and its core principles include: Proximity: Elements with close spatial distances (such as continuous lamps on the side walls of tunnels) are automatically classified as the same visual unit. Similarity: Elements that share characteristics (such as color and shape) (such as star patterns symmetrically distributed on the top) form an integrated unit. Common Fate: In dynamic scenes, elements with the same direction of movement (such as light bands when moving at high speed) are regarded as a whole. Closure: The driver fills in the missing information (such as discontinuous lighting) in his mind to form a complete perceptual object.

Further simplifying these elements into "visual elements within the visual threshold" and quantifying them into "1 landscape element" or "multiple landscape elements" is a simplified processing method based on Gestalt psychology. The advantages of this approach are: (1) Simplify complexity: avoid excessive differentiation of complex attributes such as spatial structure, color, and lighting, making the quantification process more intuitive and easy to operate. (2) Emphasize visual perception: emphasize the visual elements that the driver actually sees during driving, rather than abstract spatial attributes, so that it is closer to the actual driving situation. (3) Conform to cognitive laws: Gestalt psychology believes that human visual perception is based on the relationship between the whole and the parts, rather than isolated elements. Therefore, classifying multiple visual elements as a whole helps to better understand the driver's visual behavior.

Tunnel attributes→Sensory Input→Attention adjustment (arousal)→Cognitive assessment→Experience generation
↑____________ Feedback reinforcement ____________↓

6. CRITERIA FOR DETERMINING LANDSCAPE ELEMENTS

Table 2

Table 2 Element Determination Criteria

Visual Features	Quantification rules	Tunnel Example
Continuity	1 element	Full length evenly lit ceiling
Homogeneous repeat	1 element	Equidistant side wall light strips
Heterogeneous separation	N independent elements	Alternating plant/geometric patterns on ceiling
Functional visual blocks	1 composite element	Wall-integrated directional signage system

Source: Author

Essential differences from traditional methods: As shown in Table 3, the Gestalt quantitative model focuses on cognitive units rather than physical entities.

Table 3

Table 3 Quantitative Model

Physical Entity	Traditional Quantization	Gestalt Visual Unit	Quantization value
200m starry sky ceiling	1 Roof	Single star pattern	1
Double pattern ceiling	1 Roof	Pattern A+Pattern B	2
Side wall LED light strip sequence	N lamps	Continuous Optical Flow	1

Source: Author

7. QUANTITATIVE THEORY OF LANDSCAPE ELEMENTS

7.1. MILLER'S "MAGIC NUMBER 7 ± 2" THEORY (1956)

In a classic study, George Miller found that the capacity of human short-term memory is about 7±2 information units (chunks), such as numbers, letters, or unrelated words. This limitation stems from the bottleneck of information processing: when the amount of information exceeds this range, the accuracy of memory drops significantly. However, Miller emphasized that through the "chunking" strategy, multiple discrete information can be integrated into meaningful units (such as recording the phone number 1793528 as "179-35-28"), thus breaking through the quantity limit. For example, untrained individuals can only remember 7 random numbers, but after chunking training, they can remember more.

7.2. COGNITIVE LOAD THEORY

I Subsequent studies found that Miller's theory overestimated the actual capacity. Cowan proposed that the core limitation of working memory lies in the focus of attention, which has a capacity of only 4±1 information blocks. This conclusion is based on experimental evidence: when long-term memory interference and repetition strategies are eliminated, the number of memory items under pure attention focus stabilizes at around 4. For example, through training, the focus of attention can be expanded from 1 to 4 elements, but it is difficult to exceed this limit. This correction explains why the effective memory capacity in complex tasks (such as multi-tasking) often drops to less than 5.

7.3. COWAN'S ATTENTIONAL FOCUS CAPACITY THEORY (4 ± 1)

John Sweller proposed that working memory consists of a limited capacity central executive system and a storage subsystem:Intrinsic load, determined by the intrinsic complexity of the task (such as memorizing 5 unfamiliar symbols at the same time). External load, caused by the way information is presented (such as chaotic typesetting). Related load, cognitive resources used for deep processing. When the total load exceeds the capacity of working memory (total load = intrinsic + external + related load in the diagram), cognitive efficiency drops sharply, and the amount of information within 5 is usually in the "low load range"

8. RESEARCH METHODOLOGY

1) Case Study

Select representative domestic tunnel design cases. Collect the implementation effects of the cases and obtain relevant literature and reports. Sort out and analyze the design features of the cases and extract effective design strategies and experiences.

2) Tunnel landscape picture evaluation experiment

We selected 50 pictures (including tunnel entrance/tunnel interior/landscape belt) covering the five types of landscapes in the above cases. Sample: 40 people (drivers), drivers were stratified by driving experience: driving experience <3 years: low experience group; driving experience 3-10 years: medium experience group; driving experience >10 years: high experience group. These 40 people evaluated the 50 tunnel pictures, and the display process is shown in Figure 2.

Figure 2

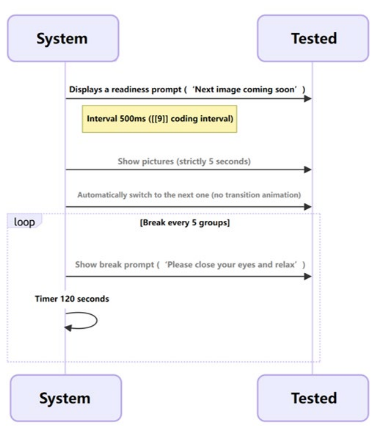


Figure 2 Picture Display Process

Source: Author

8.1. EVALUATION SCALE (TWO-DIMENSIONAL 5-POINT SCALE)

Table 4

Table 4 Two-Dimensional 5-Point Scale

Index	Very poor (1 point)	Slightly worse (2 points)	General (3 points)	Slightly better (4 points)	Very good (5 points)
Distraction - Focus					
Experience discomfort - comfort					

Source: Author

9. RESEARCH RESULTS

1) Case Study

According to China's existing standards and practical cases, the landscape design of super-long tunnels is mainly divided into the following forms (as shown in the table):

Table 5

Table 5 Statistics of Some Tunnel Landscape Designs in China

t	Tunnel name	Province	Tunnel length/ km	Design speed/ (km·h-1)	Place of landscape strip/ No.	Interval /km	Length /m	Landscape type	Completion time
1	Zhongnanshan Highway Tunnel	Shanxi	18.02	80	3	04-Jun	150	Bionic plants and lighting, blue sky and white clouds projected on the arch	2007/01
2	Micangshan Tunnel	Sichuan Shanxi	13.8	80	20			Blue sky and white clouds, colorful light strips	2018/08
3	New Erlangshan Tunnel	Sichuan	13.46	80	3	4	120	Blue sky and white clouds, five-star red flag, maple leaves	2017/09
4	Xishan Extra-long Tunne	Shanxi	13.66	80	1	6.8	200	Leaves and roots silhouettes Colored light strips	2012/10
5	Maijishan Tunnel	Gansu	12.29	80	2		Approx. 100	Colored light strips	2009/06
6	Dapingli Tunnel	Gansu	12.29	80	2	4	100	Blue sky and white clouds	2009/01
7	Chengkai Tunnel	Chong qing	11.46	80				Starry Sky	Under construction
8	Yunshan Tunnel	Shanxi	11.37	80	1	5.7	200	Colored light strips	2014/11
9	Baojiashan Tunnel	Shaanxi	11.2	80	1		Approx. 200	Blue sky and white clouds, underwater world	2009/01
10	Pagoda Mountain Tunnel	Shanxi	10.48	80	2	3.5	200	Colored light strips	2011/12
11	Zhongtiaoshan Tunnel	Ningxia	9.61	80	1			Colored light strips	2014/07
12	Liupanshan Tunnel	Yunnan	9.49	80	1	5	200	Underwater world, blue sky and white clouds	2016/07
13	Yanglin Tunnel	Sichuan	9.46	80	1	4.7	150	Landscape scroll	2020/10

14	Baoding No. 2 Tunnel	Jilin	8.8	80	2	3	120	Blue sky, white clouds, stone scenery, artificial plants and colorful light strips	2019/12
15	Wunvfeng Tunnel	Guangdong	7. 93	60	1	4	120	Blue sky, white clouds, colorful light strips	2018/11
16	Maluanshan Tunnel	Chongqing	7.9	80	2		100, 200	Natural cave landscape, Sea World, Pingshan scenery	2019/09
17	Qiganshan Tunnel	Chongqing	7.63	80	1	3.6	300	Mountains and rivers, four seasons scenery, humanities and natural landscapes	Under construction
18	Huayan Tunnel	Hunan	7.1	60	4	1	100	Blue sky and white clouds	2017/12
19	Xuefengshan Tunnel	Chongqing	7.04	80	1	03-Apr		Blue sky and white clouds	2007/11
20	Grape Mountain Tunnel	Jiangsu	6.3	80	1	3	20	Colored light strips	2009/06
21	Dushuhu Lake Tunnel	Suzhou	3.46	80	2			Colored light strips	2007/10

Source: Author

9.1. LANDSCAPE TYPE DISTRIBUTION PATTERN

(1) Dominant type (accounting for 68%)

Artificial light environment: colored light strips (12 strips)

Natural simulation: blue sky and white clouds (14 strips)

Combined design trend: after 2015, 60% of tunnels use a combination of two or more types (such as Baoding No. 2 Tunnel, which combines four elements).

9.2. INNOVATION TYPE (EMERGING SINCE 2016)

Table 6

Table 6 Innovation Type

Type	Representative Tunnel	Design Features
Immersive ecological scene	Liupanshan Tunnel	Underwater World + Dynamic Light and Shadow
Humanities Theme Narrative	New Erlangshan Tunnel	Five-star red flag + maple leaf red culture
Full Dome Simulation	Chengkai Tunnel	"Starry Sky"
Dynamic changes of seasons	Qiganshan Tunnel	Landscapes change synchronously with seasons

Source: Author

9.3. REGIONAL CHARACTERISTICS MAPPING

1) Southwest Tunnel: Many landscape themes ,such as Yanglin Tunnel "Landscape Painting". Figure 3

Figure 3

Figure 3 Yanglin Tunnel

Source: Author

2) Northwest Tunnel: Blue sky and white clouds in the middle (compensating for the lack of natural light).

3) Coastal tunnels: Introducing marine elements, such as Maluanshan Tunnel "Sea World". Figure 4

Figure 4

Figure 4 Maluanshan Tunnel

Source: Author

9.4. CRITICAL VALUE PHENOMENON

When the tunnel length is ≥10km, 83% of them have ≥2 landscape belts (Grape Mountain Tunnel has 1 landscape belt at 6.3km as an exception). Speed constraint: The landscape complexity of 60km/h tunnel is higher (Huayan Tunnel has 4 landscape belts/7.1km vs 80km/h with an average of 1.5 landscape belts).

2) Tunnel landscape elements evaluation research data

Step 1: 50 tunnel landscape images × 40 participants × 2 dimensions (attention, experience) = 4,000 scoring data points.

Step 2: Each image was manually annotated by the research team in advance to determine the number of landscape elements it contained and divided into 4 groups:

Table 7

Table 7 Image Evaluation

Number of elements interval	Number of pictures	Total number of scores per group
1–3	≈10 sheets	10×40×2 = 800
4–5	≈15 sheets	15×40×2 = 1200
6–9	≈15 sheets	15×40×2 = 1200
>9	≈10 sheets	10×40×2 = 800

Source: Author

Step 3: Count the score distribution of each group.

Formula:

$$\text{Percentage} = \frac{\text{Number of occurrences of a rating}}{\text{Overall rating score}} \times 100\%$$

Step 4: Use pie charts to show the score distribution of attention and experience (1-5 points).

1) 1-3 elements: attention and experience.

Figure 5

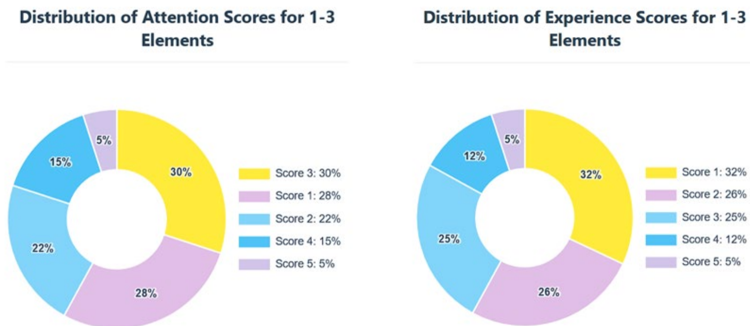


Figure 5 1-3 Elements: Attention and Experience

Source: Author

2) 4-5 elements: attention and experience

Figure 6

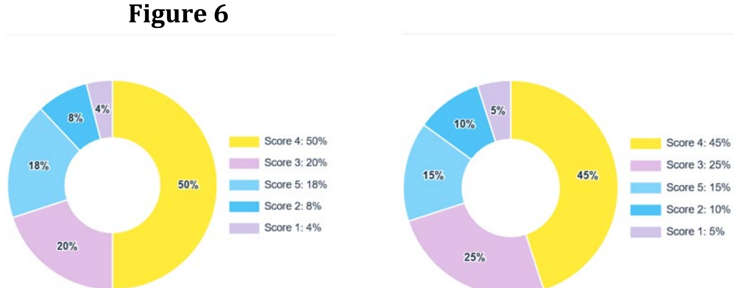


Figure 6 4-5 Elements: Attention and Experience

Source: Author

3) 6-9 elements: attention and experience

Figure 7

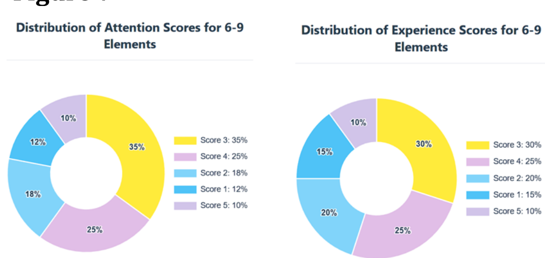


Figure 7 6-9 Elements: Attention and Experience

Source: Author

4) >9 elements: attention and experience

Figure 8

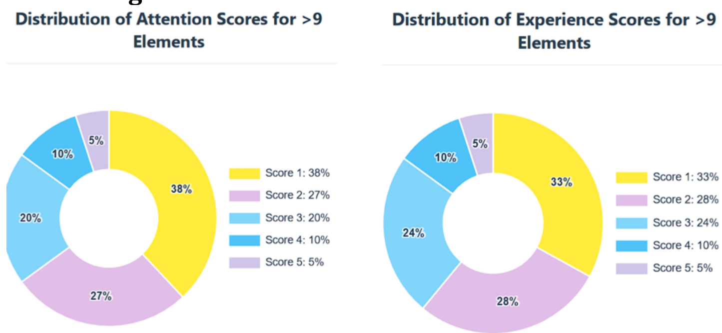


Figure 8 >9 Elements: Attention and Experience

Source: Author

Step 5: Quantitative results

1) The relationship between the number of landscape elements and attention:
   - When the number of landscape elements is 1-3, the driver's attention is significantly reduced, the concentration is low, and fatigue is easy to occur.
   - When the number of landscape elements is 4-5, the driver's attention is significantly improved, the concentration is high, and the driving experience is significantly improved.
   - When the number of landscape elements is 6-9, although the driver's attention is increased, the attention is scattered, resulting in a decrease in driving experience.
   - When the number of landscape elements exceeds 9, the driver's attention is further scattered, the visual load increases, and driving safety decreases.
2) The relationship between the number of landscape elements and emotions:
   - Too few landscape designs (1-3 elements) can easily make the driver feel bored and tired, and depressed.
   - Moderate landscape designs (4-5 elements) can effectively improve the driver's emotional state and reduce anxiety and tension.
   - Too many landscape designs (6-9 elements) may cause emotional fluctuations in the driver and increase driving pressure.
   - Overloaded landscape designs (>9 elements) are prone to cause emotional anxiety in the driver.
3) The relationship between the number of landscape elements and visual load:
   - Too few landscape designs (1-3 elements) may lead to excessive visual load and increase driving fatigue.
   - Moderate landscape designs (4-5 elements) can effectively reduce the driver's visual load and improve driving safety.
   - Too many landscape designs (6-9 elements) will increase the driver's visual load, leading to distraction and increased driving risks.
   - Overloaded landscape designs (>9 elements) will cause visual overload and lead to driving safety risks.

Figure 9

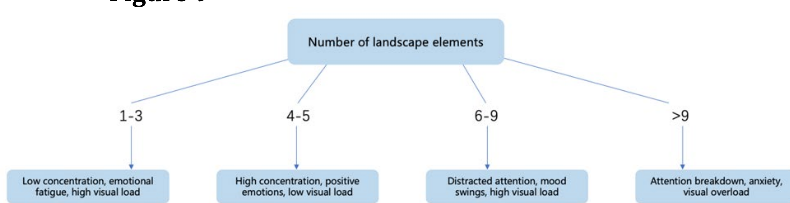


Figure 9 The Relationship Between Landscape Element Quantification and Attention, Emotion, and Cognitive Load

Source: Author

Moderate landscape design (4-5 elements) can effectively improve the driver's attention and mood, reduce visual load, and improve driving safety. Too much or too little landscape design will have a negative impact on driving safety and should be avoided.

10. CONCLUSIONS AND DISCUSSION

Based on 40 drivers of different driving experience and 4,000 attention-experience evaluations of 50 super-long tunnels, this study combined Gestalt psychology and cognitive load theory to give a quantitative relationship between "number of landscape elements-driving emotional performance (attention and experience)", and proposed feasible optimization guidelines for tunnel visual landscape. The main findings and implications are discussed as follows.

1) Re-examination of core findings

- "4-5 elements" is the golden interval for safety and experience win-win. At this time, the proportion of attention ≥ 4 points reached 68%, and the proportion of experience ≥ 4 points accounted for 60%, which was significantly higher than the other intervals ($p < 0.01$). This result is highly consistent with the "4±1" attention focus capacity proposed by Cowan, proving that driving scenarios also have an upper limit of working memory.
- "Too little is overload" phenomenon. The high visual load in the 1-3 element interval does not come from complexity, but from the active search load caused by the "information desert", which is passive fatigue.
- "Too much is distraction" phenomenon. In the 6-9 element interval, cognitive load increases and attention is easily distracted.
- "Overload" phenomenon. In the interval of >9 elements, the number of elements continues to increase, which is easy to cause mental stress and cognitive confusion, which is consistent with the high incidence of accidents.
- The emotional dimension changes synchronously. The anxiety scale score of the interval of 4-5 elements is the lowest, while there are significant differences between the intervals of 1-3 and >9, indicating that landscape moderation is not only related to attention, but also to emotional homeostasis.

2) Dialogue with existing research

Traditional tunnel landscape research focuses on "light-dark" adaptation or single color intervention, ignoring the "total" effect of the number of elements. This paper transforms the Gestalt concept of "blocking" into an operational "element counting" method, breaking through the bottleneck of the "physical component-visual perception" split. Compared with the "minimalist black, white and gray" or "all-LED media wall" polar practices commonly used in foreign high-speed tunnels, this study has found a quantitative basis for "moderate complexity" and can directly guide the formulation of design standards. When the emotional dimension is given the same weight as structural safety, the ultra-long enclosed space is transformed into a continuous "psychological healing field". The future tunnel is no longer just a passage through the mountain, but an emotional infrastructure that can be read, experienced and cured, truly realizing the dual arrival of "safety + pleasure".

CONFLICT OF INTERESTS

None.

ACKNOWLEDGMENTS

Researcher would like to express her sincere to the thesis advisor, Asst. Prof. Dr. Chanoknart Mayusoh for her invaluable help and constant encouragement throughout the course of this research. In addition, the researcher has to give thanks to all lecturers for their assistance: Asst. Prof. Dr. Akapong Inkuer and Asst. Prof. Dr. Pisit Puntien. At the same time, the researcher gratefully thanks to Miss Sasanant Rattanapornpisit, Mr. Chat Sukarin, Miss Vistha Chintaladdha, Miss Kanyanee Phangsua, etc. for their strong support.

Finally, the researcher would like to express her gratitude to Suan Sunandha Rajabhat University School of Fine and Applied Arts for their support in all aspects.

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