

Article

Winter Visual Perception Mechanisms in Cold-Region Outdoor Public Spaces: A Built-Environment Framework for Eye-Tracking-Based Evaluation and Design

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Abstract

Outdoor public spaces are important built-environment settings that support health, social interaction, psychological restoration, and everyday urban life. In cold-region cities, however, winter conditions such as low temperature, snow and ice, short daylight, reduced vegetation, low solar altitude, and declining outdoor activity substantially weaken their usability, attractiveness, and vitality. Existing studies have mainly addressed these problems through thermal comfort, microclimate adaptation, snow safety, and physical environmental optimization, but they provide limited explanation of how users visually perceive winter spaces, allocate attention, and form subsequent spatial interpretations, perceptual evaluations, and behavioral intentions. To address this gap, this conceptual article develops a built-environment framework for explaining winter visual perception mechanisms and proposes an agenda for future eye-tracking-based validation. Through conceptual synthesis across cold-region public-space research, outdoor thermal comfort, environmental psychology, landscape visual perception, eye-tracking studies, public-space behavior, and architectural and built-environment design, the study conceptualizes winter public spaces as seasonal perceptual environments. It identifies five categories of winter visual stimuli: surface-related, vegetation-related, building interface-related, lighting-related, and activity-related stimuli. The framework clarifies how visual attention may serve as an observable mediating process between winter visual stimuli and inferred spatial interpretation, perceptual evaluation, and behavioral intention. Rather than empirically confirming these relationships, the article formulates a testable conceptual model and future validation agenda that should be examined through eye-tracking, behavioral observation, subjective evaluation, and environmental measurements. For architectural and built-environment research, the framework provides a theoretical basis for evaluating and optimizing façades, ground-floor interfaces, entrances, canopies, semi-outdoor spaces, path boundaries, lighting systems, vegetation configuration, and winter activity nodes.



Academic Editor: Cinzia Buratti

Received: 21 June 2026

Revised: 9 July 2026

Accepted: 10 July 2026

Published: 12 July 2026

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Keywords: winter public spaces; cold-region cities; visual attention; visual perception mechanism; eye tracking; built-environment design; environmental perception

1. Introduction

Against the backdrop of deepening research on climate change, healthy cities, and human-centered built environments, outdoor public spaces have become an important research object linking urban environmental quality, residents' health, and everyday behavior. Public spaces are no longer merely objects of urban form organization or landscape

beautification; rather, they serve as important spatial carriers that influence residents' physical activity, social interaction, psychological restoration, and environmental equity [1–6]. Accordingly, the focus of public-space research has gradually shifted from spatial provision and facility configuration toward comfort experience, health support, behavioral promotion, and human-centered evaluation. Within this shift, outdoor thermal comfort, microclimate regulation, and environmental performance evaluation have become important research directions [7–15]. However, when the evaluation of public spaces relies primarily on environmental parameters, simulation results, and comfort thresholds, the process through which users visually notice spatial cues, interpret them, and form perceptual evaluations or behavioral intentions can still easily be reduced to questionnaire results or user-evaluation variables [16].

In cold-region cities, winter climate and seasonal environmental conditions further amplify the decline in the use of outdoor public spaces, landscape attractiveness, and the vitality of public life. Factors such as low temperatures, snow accumulation, ice formation, strong winds, insufficient sunlight, and short daytime duration reduce the thermal comfort, pedestrian safety, and staying potential of public spaces [17,18]. At the same time, seasonal vegetation decline, monotonous colors, and weakened landscape layering also reduce spatial attractiveness. As a result, winter public spaces face not only questions of “whether they are cold” and “whether they are walkable,” but also questions of “whether people are willing to enter,” “whether people are willing to stay,” and “whether they are attractive.” Existing studies on severe-cold cities have shown that winter outdoor spatial experience is not a single thermal-environment issue, but is jointly influenced by multisensory comfort, including visual, thermal, and acoustic comfort [19,20]. This suggests that research on winter public spaces in cold-region cities needs to move beyond thermal comfort and microclimate optimization to further address human perceptual experience and behavioral choice.

Existing studies on outdoor public spaces in cold-region cities have mainly explained winter space-use problems from the perspectives of thermal comfort, microclimate adaptation, and physical environmental optimization. Related studies commonly employ on-site meteorological monitoring, thermal comfort questionnaires, thermal sensation voting, evaluation indices such as PET and UTCI, as well as ENVI-met or other numerical simulation methods, to examine air temperature, wind speed, solar radiation, mean radiant temperature, and users' thermal sensation or comfort votes in winter settings [21–25]. These studies have established a relatively solid knowledge base concerning the relationship between “climatic environment–thermal comfort evaluation–space use,” and they are essential for determining whether outdoor spaces provide the basic physical conditions for winter use.

However, the usability of winter public spaces cannot be fully explained by thermal acceptability alone. A space may be thermally improved but still be avoided if its paths are visually unclear, its entrances are difficult to identify, its snow-covered or icy surfaces appear risky, its lighting is insufficient, or its activity cues are weak. Conversely, a space with less favorable microclimatic conditions may still attract use when visible sunlight, cleared paths, active edges, recognizable entrances, or visible social activity provide cues of accessibility, safety, and vitality. Therefore, thermal-comfort-oriented studies are less able to explain how users visually detect winter spatial cues, allocate attention to risks or opportunities, and form early judgments about whether a space is enterable, stayable, or worth revisiting.

This limitation does not reduce the importance of thermal comfort research. Rather, it indicates that thermal comfort explains the physical suitability of winter public spaces, whereas visual attention helps explain the perceptual process through which users recognize, interpret, and respond to winter spatial conditions. For this reason, a more complete

understanding of winter public-space usability requires a complementary mechanism that links winter-specific visual stimuli with observable attention processes and inferred spatial interpretation.

This article further argues that winter visual stimuli constitute an insufficiently theorized pathway for understanding winter public-space usability. Existing visual perception and eye-tracking studies have provided important evidence on landscape preference, restorative experience, streetscape perception, and attention to environmental elements in streets, parks, and landscapes [26,27]. These studies show that visual elements influence how people evaluate outdoor environments, but they do not yet provide a winter-specific explanation of how snow cover, high-brightness ground surfaces, vegetation decline, color monotony, low solar altitude, long shadows, strengthened building interfaces, lighting dependence, and reduced activity cues reorganize users' visual attention in cold-region public spaces.

This gap is particularly important because winter changes not only the microclimate of public spaces but also the visibility, salience, and interpretability of spatial cues. Snow may brighten the ground while blurring path boundaries; ice may create visible risk cues; leaf fall and color monotony may reduce landscape richness; low solar altitude and long shadows may complicate spatial orientation; and reduced outdoor activity may make visible people, entrances, lighting nodes, and active interfaces more important for judging accessibility and social safety. These visual conditions are closely related to whether users perceive a space as clear, safe, attractive, and usable, but they are not sufficiently captured by thermal-comfort indices or by general landscape preference studies.

Therefore, the research gap addressed in this article is not simply the absence of studies on winter comfort or visual preference. Rather, it is the lack of a focused framework explaining how winter-specific visual stimuli are selected through observable visual attention and how this attention process may support subsequent spatial interpretation and behavioral intention. This provides the basis for developing an eye-tracking-informed conceptual framework for future empirical validation in cold-region winter public spaces.

Based on this refined research gap, this article develops a conceptually derived and eye-tracking-informed framework for explaining a focused mechanism in cold-region winter public spaces: how winter-specific visual stimuli are selectively attended to and how this attention process may support subsequent spatial interpretation and behavioral intention. Unlike studies that primarily evaluate whether winter spaces are thermally comfortable, visually preferred, or generally satisfactory, this article focuses on the intermediate attention process through which visible winter cues are noticed, filtered, and cognitively organized before users form judgments of safety, legibility, attractiveness, and possible action.

Within this narrowed scope, the primary contribution of the article is the development of a theoretical framework. The framework positions visual attention as an observable mediating process between winter visual stimuli and users' subsequent interpretation of safety, legibility, attractiveness, and possible action. Eye-tracking is therefore not used here as direct evidence of emotional states or behavioral outcomes, but as a process-oriented approach for identifying what users visually notice, revisit, or overlook in winter public spaces.

The contribution structure of this article is deliberately organized around a primary theoretical contribution and a secondary application-oriented extension. The primary contribution is the development of a winter visual-attention mechanism that links winter-specific visual stimuli, observable visual attention, inferred spatial interpretation, perceptual evaluation, and behavioral intention. The design-related discussion is positioned as a secondary translation of this conceptual framework rather than an independent theoretical contribution or a prescriptive design guideline. Building façades, ground-floor interfaces, entrances,

canopies, semi-outdoor spaces, path boundaries, lighting systems, vegetation configuration, and winter activity nodes are discussed as built-environment variables through which the proposed visual-attention mechanism may be evaluated, diagnosed, or tested in future studies. In this way, the article clarifies its primary contribution as framework development, while design implications and empirical validation directions serve as extensions of this core mechanism. To clarify the theoretical advancement of this article in relation to existing cold-region public-space research, Figure 1 summarizes the research logic, main conceptual gap, and framework-building direction of the study.

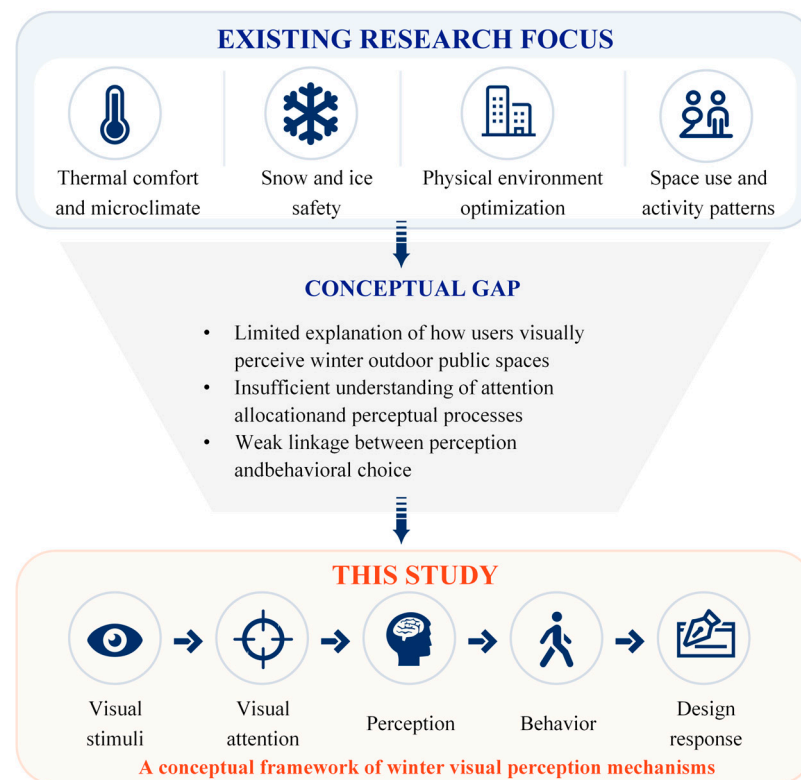


Figure 1. Research logic, conceptual gap, and contribution to seasonal urban design models.

2. Conceptual Synthesis and Framework-Building Procedure

This article is positioned as a conceptual framework article based on integrative conceptual synthesis rather than as a systematic review or an empirical hypothesis-testing study. Its purpose is not to quantify the effect size of winter visual stimuli or to verify causal relationships through primary data, but to construct a theoretically grounded and empirically testable explanatory framework for future research. To improve methodological transparency, the literature was selected according to three relevance criteria. First, it had to address cold-region or winter public-space conditions, outdoor thermal comfort, seasonal urban design, or winter space-use constraints. Second, it had to contribute concepts related to visual perception, visual attention, eye-tracking indicators, environmental psychology, or public-space behavior. Third, it had to provide built-environment variables or design-related constructs relevant to public-space usability, such as façades, entrances, lighting, vegetation, paths, activity nodes, or semi-outdoor spaces. The literature that was unrelated to winter public spaces, visual or perceptual processes, or built-environment evaluation was not used as a conceptual source for framework construction.

The framework-building process consists of three linked steps. First, relevant literature domains were identified and grouped into cold-region public-space research, outdoor thermal comfort, environmental psychology, landscape visual evaluation, eye-tracking

studies, public-space behavior, and architectural and built-environment design. Second, core concepts were extracted from these domains, including winter environmental constraints, winter visual stimuli, observable visual attention, perceived safety, spatial legibility, attractiveness, restorative potential, behavioral intention, and design response. Third, these concepts were reorganized into a mechanism chain that moves from the cold-region winter environment, through winter visual stimuli and observable visual attention, to inferred spatial interpretation, perceptual evaluation, behavioral intention, and design translation. Through this synthesis, the article explains how winter visual stimuli may support spatial interpretation, perceptual evaluation, and behavioral intention through visual attention, and how these relationships could be examined in future eye-tracking-based studies.

2.1. Conceptual Synthesis Procedure

To construct a framework for visual perception mechanisms in winter outdoor public spaces of cold-region cities, this article adopts a three-step conceptual synthesis approach. First, the literature domains were identified when they addressed at least one of the following aspects: cold-region winter environmental conditions, visual or multisensory perception, eye-tracking-based attention measurement, public-space behavior, or built-environment design variables. Second, core concepts were extracted from these domains according to their function in the proposed mechanism. Concepts describing environmental conditions were grouped as winter environmental constraints; concepts describing visible seasonal elements were grouped as winter visual stimuli; concepts describing gaze allocation were grouped as observable visual attention; concepts describing perceived safety, legibility, attractiveness, restoration, or comfort were grouped as perceptual evaluation and spatial interpretation; and concepts describing entering, staying, avoiding, revisiting, or activity participation were grouped as behavioral intention or outdoor-space use. Third, these concepts were reorganized into a mechanism chain moving from the cold-region winter environment, through winter visual stimuli and observable visual attention, to inferred spatial interpretation, perceptual evaluation, behavioral intention, and design translation. This process allowed the framework to move from literature-domain identification to concept extraction, conceptual clustering, and mechanism integration.

A key requirement of a conceptual article is to clearly explain the sources of concepts, theoretical choices, and analytical logic [28]. Therefore, this article does not simply juxtapose the literature from different fields. Instead, it reorganizes relevant concepts around the core question of “how environmental cues are seen, selected through visual attention, interpreted, and potentially transformed into spatial or behavioral responses.” The conceptual synthesis was conducted not only by extracting concepts from each literature domain, but also by identifying the limitations and unresolved relationships among them.

Specifically, three critical relationships guided the synthesis. First, cold-region public-space and outdoor thermal-comfort studies provide strong explanations of physical suitability, but they are less able to explain how users visually recognize winter risks, accessibility, and activity opportunities. Second, environmental psychology and public-space behavior studies explain perceived safety, attractiveness, restoration, and behavioral intention, but they often treat these constructs as perceptual outcomes rather than clarifying the preceding attention process. Third, visual perception and eye-tracking studies provide process-based indicators of gaze behavior, but they have rarely been integrated with winter-specific environmental constraints and built-environment design variables in cold-region public spaces.

To improve the transparency and critical depth of the conceptual synthesis, Table 1 summarizes not only the conceptual contribution of each literature domain, but also its main limitations and the unexplored relationships that motivate the proposed framework. The

table does not function as a systematic review protocol because the purpose of this article is conceptual framework development rather than exhaustive evidence aggregation. Rather, it clarifies the conceptual sources, extracted constructs, critical gaps, and framework-building roles of the reviewed literature domains. Figure 2 further illustrates how the framework was developed from literature-domain identification and concept extraction toward critical synthesis, mechanism integration, and future eye-tracking-based validation.

Table 1. Literature domains, extracted concepts, critical gaps, and roles in framework construction.

Literature Domain	Key Concepts Extracted	Critical Limitation or Unexplored Relationship
Cold-region public-space research	Low temperature, snow cover, ice formation, wind exposure, short daylight, reduced activity	Explains winter constraints and seasonal decline in use, but less often examines how these conditions reorganize visual attention and spatial interpretation
Outdoor thermal comfort research	PET, UTCI, microclimate adaptation, solar radiation, wind shelter, comfort evaluation	Provides strong evidence on physical suitability, but cannot fully explain visually mediated judgments of accessibility, safety, attractiveness, or stayability
Environmental psychology	Perceived safety, comfort, attractiveness, restoration, legibility, behavioral intention	Explains perceptual and behavioral outcomes, but often leaves the preceding attention-selection process under-specified
Landscape visual perception	Seasonal preference, visual aesthetics, vegetation perception, snow landscape perception	Addresses visual preference and seasonal landscape evaluation, but less directly links winter-specific visual cues to public-space usability and behavioral intention
Eye-tracking studies	Fixation duration, fixation count, time to first fixation, saccade path, AOI, heat map, pupil response	Provides process-based attention indicators, but is often used descriptively and rarely connected to cold-region winter constraints or built-environment design variables
Public-space behavior research	Entering, staying, walking, gathering, avoiding, revisiting, activity participation	Links space and behavior, but usually relies on observed outcomes rather than explaining how visual cues are attended to before action
Architectural and built-environment design	Building façades, ground-floor interfaces, entrances, canopies, semi-outdoor spaces, lighting, path boundaries	Provides operable design variables, but often lacks a mechanism explaining how these variables are visually perceived and interpreted in winter

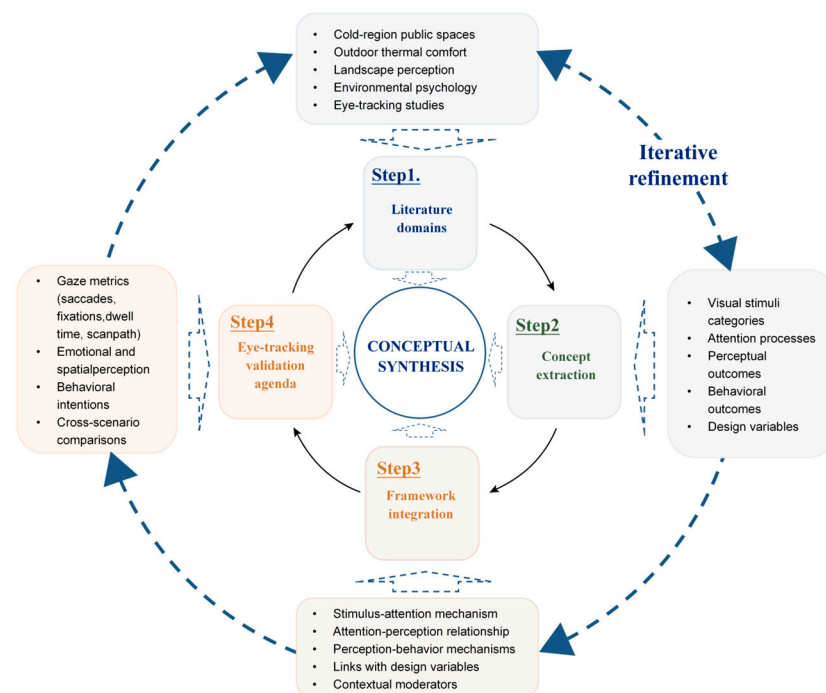


Figure 2. Conceptual synthesis and validation procedure for framework development.

Taken together, the reviewed literature reveals not only three foundations but also three unresolved connections that motivate the proposed framework. Cold-region public-space and outdoor thermal-comfort studies define the winter environmental context and clarify how low temperature, wind exposure, solar radiation, snow safety, spatial form, and user adaptation influence the physical suitability of winter spaces [21,23,24,29–31]. However, these studies mainly explain whether winter spaces provide acceptable physical conditions for use, while providing less explanation of how users visually identify risks, entrances, paths, activity cues, and stayable locations.

Visual perception, landscape evaluation, and eye-tracking studies provide a processual perspective for explaining how users identify spatial elements through looking, searching, fixating, and comparing before forming landscape preferences or spatial judgments [32–35]. However, these studies are often conducted in general streets, parks, landscapes, or controlled visual scenes and have not sufficiently addressed how winter-specific cues such as snow reflection, blurred path boundaries, low solar altitude, long shadows, vegetation decline, lighting dependence, and reduced outdoor activity reshape attention allocation in cold-region public spaces.

Environmental psychology and public-space behavior research further explain how perceived safety, comfort, attractiveness, legibility, restoration, and activity expectations are related to outcomes such as entering, staying, walking, gathering, avoiding, or revisiting [36,37]. However, the link between environmental cues and behavioral outcomes is often inferred from subjective evaluation or observed behavior, while the intermediate attention process remains insufficiently specified. Therefore, the key unexplored relationship lies in how winter-specific visual stimuli are selected through observable visual attention and how this process may support subsequent spatial interpretation and behavioral intention. Based on this critical synthesis, this article extends cold-region public-space research from a thermal-comfort-oriented and outcome-oriented explanation toward a focused visual-attention mechanism.

The proposed mechanism is further anchored in four established theoretical perspectives. Attention restoration theory helps explain why visually salient natural elements, winter landscape focal points, and reduced visual fatigue may be related to restorative interpretation. Environmental preference theory supports the role of coherence, legibility, complexity, and visual order in shaping users' spatial interpretation and preference. Place attachment theory provides a basis for understanding how familiar entrances, visible social activity, seasonal activity nodes, and recognizable public-space interfaces may contribute to the meaning of place and emotional connection. Affordance theory further explains how visible environmental cues indicate possible actions, such as entering, walking, staying, gathering, or avoiding. These theories are not treated as separate explanatory models in this article; rather, they serve as theoretical anchors for different links in the proposed pathway from winter visual stimuli to observable visual attention, inferred spatial interpretation, and behavioral intention.

2.2. Cold-Region Winter Public Spaces as Seasonal Perceptual Environments

Winter outdoor public spaces in cold-region cities should not be regarded merely as objects of climatic adaptation, but should also be understood as perceptual environments with distinct seasonal visual and behavioral characteristics. Traditional research on cold-region public spaces usually gives primary attention to the effects of low temperature, wind environment, solar radiation, snow accumulation, and ice formation on space use, because these factors directly determine whether winter spaces provide basic thermal comfort, pedestrian safety, and staying potential. However, from the perspective of human spatial experience, the cold-region winter environment is not merely an external condition that

causes thermal discomfort. It also reshapes how people identify spaces and anticipate their use by changing ground-surface conditions, spatial boundaries, landscape colors, visual organization, and the visibility of activities.

The seasonal perceptual characteristics of cold-region winter public spaces are mainly reflected in simultaneous changes in spatial accessibility, stayability, and legibility. Low temperature, wind chill, snow accumulation, and ice formation affect pedestrian safety, route choice, and willingness to stay. Short daytime duration, long nights, low solar altitude, and long shadows change the patterns of light and shadow relationships of spaces, making the visual presentation of building interfaces, ground paving, vegetation, and activity facilities significantly different from that in non-winter seasons. Leaf fall, reduced greenery, and color monotony further decrease landscape richness, making winter public spaces more dependent on building interfaces, lighting, activity cues, and path recognition to maintain spatial attractiveness [17,18,38]. For older adults, children, and other groups who are more sensitive to safety and comfort, path clarity, visible staying points, wind-sheltered spaces, sunlit spaces, nighttime lighting, and recognizable activity cues in winter spaces all influence whether they are willing to enter, stay, and participate in activities [39–42]. Therefore, cold-region winter public spaces should be understood not only as climate-adaptive spaces shaped by low temperature, wind exposure, snow safety, and solar access, but also as seasonal perceptual environments in which visual cues influence accessibility, stayability, and spatial legibility. Snow reflection, blurred path boundaries, low solar altitude, long shadows, vegetation decline, lighting dependence, and reduced activity cues may generate attention patterns that differ from those in non-winter or non-snowy environments. Figure 3 summarizes these winter-specific visual conditions and their expected implications for gaze response and interpretation.

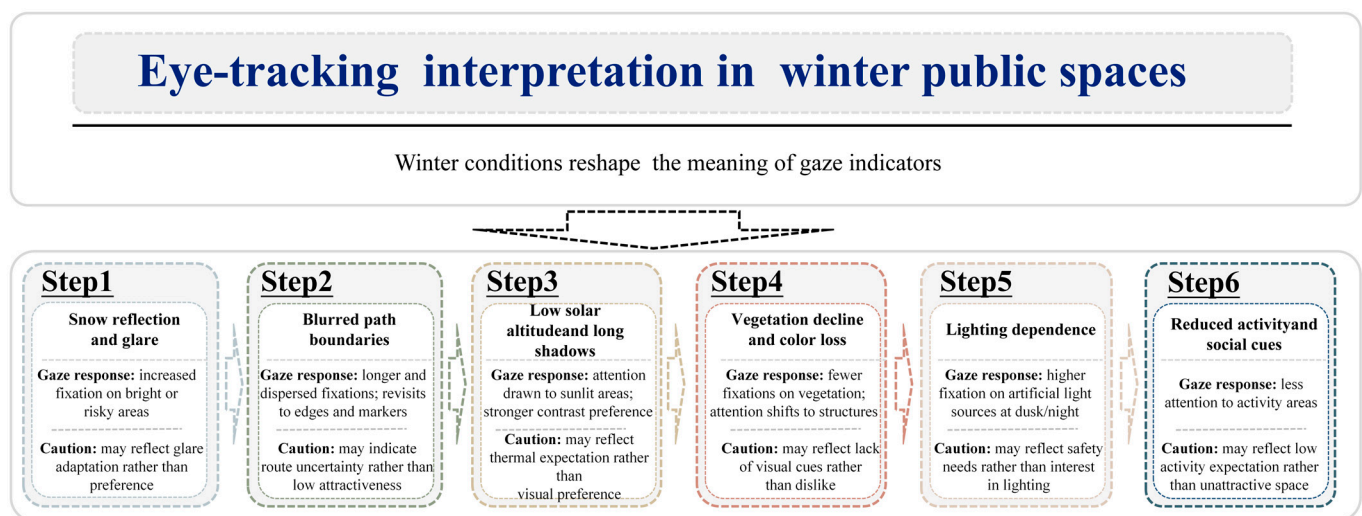


Figure 3. Winter-specific visual conditions and expected attention mechanisms.

2.3. Winter Visual Stimuli and Visual Attention as a Mechanism

Within this seasonal perceptual environment, winter visual stimuli refer to visible cues through which users identify paths, boundaries, risks, activity opportunities, and staying possibilities. These stimuli include ground-surface changes, vegetation phenology, built interfaces, lighting conditions, and visible activity cues. Existing studies on seasonal landscape preference, snow reflection, winter and summer vegetation perception, and the visual appearance of snow have shown that seasonal change, snow cover, and vegetation conditions can alter visual aesthetics, reflective characteristics, and environmental preferences [43–46]. However, these studies mainly clarify how specific seasonal elements affect visual appearance or preference, while less attention has been given to how multiple winter

cues jointly organize attention allocation and usability judgments in public-space settings. Building on this limitation, this article treats winter visual stimuli not merely as visual landscape attributes, but as perceptual cues that may guide attention toward paths, boundaries, risks, entrances, lighting nodes, activity opportunities, and staying possibilities.

Visual attention is hypothesized to function as the central mediating process in the proposed framework. More specifically, winter visual stimuli are first selected through gaze allocation, fixation, revisiting, and visual search; these observable attention processes may then inform users' interpretation of spatial safety, legibility, attractiveness, and possible action. The framework therefore does not assume that winter visual stimuli automatically determine emotional perception or behavioral choice. Instead, it focuses on the intermediate process through which visible winter cues are noticed, filtered, and cognitively organized before perceptual or behavioral responses are formed [47]. Eye-tracking indicators are used in this framework to represent observable visual attention rather than psychological outcomes themselves. Their value lies in supplementing traditional thermal-comfort evaluation and subjective questionnaires by revealing which winter spatial elements users notice early, revisit repeatedly, or overlook. In this sense, the proposed mechanism is narrower than a full multisensory model of winter public-space experience. Thermal and acoustic conditions remain important, but in this article they are treated as contextual dimensions that may interact with visual cues rather than as additional mechanisms to be explained in parallel.

For example, sunlit areas, wind-sheltered corners, visible seating, snow-cleared paths, and active nodes may visually suggest warmth, usability, or social safety, whereas shaded, icy, empty, or poorly lit areas may visually suggest risk or avoidance. These examples are used to illustrate how visual cues may support interpretation; they are not presented as empirically verified causal effects. Future studies should combine eye-tracking with subjective evaluation, behavioral observation, thermal measurements, and acoustic assessment to test these relationships.

3. Conceptual Framework: Winter Visual Perception Mechanisms

Based on the above conceptual synthesis, this article proposes a focused conceptual framework for winter visual perception mechanisms in outdoor public spaces of cold-region cities. The framework does not attempt to explain the full multisensory experience of winter public spaces, nor does it claim that eye-tracking indicators can directly measure emotional states or behavioral outcomes. Instead, it focuses on a specific mechanism: how winter visual stimuli influence observable visual attention, and how this attention process may then support users' spatial interpretation, perceived safety, legibility, perceptions of attractiveness, and behavioral intention.

The framework consists of three interrelated components. The first component identifies the main types of winter visual stimuli in cold-region public spaces. The second component clarifies how selected eye-tracking indicators can represent observable visual attention processes. The third component explains how visual attention may serve as an intermediate process between environmental cues and inferred perceptual or behavioral constructs. The theoretical logic of these components is informed by attention restoration theory, environmental preference theory, place attachment theory, and affordance theory: restoration and preference theories support the interpretation of attractiveness, legibility, and restorative potential; place attachment theory helps explain the role of familiar and socially meaningful winter cues; and affordance theory links visible cues with perceived possibilities for action. In this way, the framework narrows the analytical focus from the broad multisensory experience of winter public spaces to a testable visual-attention mechanism.

3.1. Classification of Winter Visual Stimuli

Winter visual stimuli in outdoor public spaces of cold-region cities can be classified into five types: surface-related, vegetation-related, building interface-related, lighting-related, and activity-related stimuli. This classification is not directly derived from a fixed typology in any single existing study. Rather, it was derived through a cross-mapping of three dimensions: winter-specific environmental changes, visible spatial elements, and their potential perceptual functions for users.

To reduce conceptual overlap, the classification follows a primary-source and dominant-function rule. Each visual cue is assigned to the category that best represents its main source in the winter scene and its dominant perceptual function in the proposed framework. Surface-related stimuli refer to ground and walking-surface conditions; vegetation-related stimuli refer to seasonal plant and landscape conditions; building interface-related stimuli refer to relatively stable architectural and spatial boundary elements; lighting-related stimuli refer to visible light, shadow, glare, and illumination conditions; and activity-related stimuli refer to visible signs of use, social presence, and behavioral opportunities. Where one spatial element could belong to more than one category, it is classified according to its dominant perceptual role. For example, an entrance is treated as a building interface-related stimulus when it primarily supports orientation, accessibility judgment, or boundary recognition, but activities occurring around an entrance are treated as activity-related stimuli when they primarily signal social presence or behavioral opportunity. Similarly, a commercial frontage is treated as a building interface when its physical transparency, façade order, or ground-floor openness is emphasized, but is treated as an activity-related stimulus when visible people, displays, or ongoing use are the main perceptual cues. Lighting is treated as a visual stimulus in this classification when it shapes visibility, contrast, shadow, glare, or detectability, while lighting systems are discussed later as design variables only in the design-translation section.

Specifically, snow cover, ice surfaces, and high-brightness ground surfaces were grouped as surface-related stimuli because they reflect winter ground conditions and light-reflection characteristics. Vegetation phenology, reduced greenery, and exposed branches were grouped as vegetation-related stimuli because they reflect changes in winter landscape structure and visual attractiveness. Building façades, ground-floor interfaces, street-wall continuity, and semi-outdoor spaces indicate the increased visual weight of built-environment interfaces after the weakening of natural landscapes in winter. Low solar altitude, long shadows, nighttime lighting, and lighting nodes were grouped as lighting-related stimuli because they influence visibility, orientation, and perceived safety. Visible people, winter facilities, commercial interfaces, and ice–snow activity cues represent the visualized expression of behavioral possibilities and place vitality in public spaces [33,35,37,41,43–46,48–54].

The basis for this classification mainly comes from five research foundations: studies on seasonal landscape preference and vegetation perception support vegetation-related stimuli [42,44,51,54]; studies on snow reflection and the visual appearance of snow support surface-related stimuli [41,43,52,53]; studies on urban design qualities and streetscape complexity support building interface-related stimuli [35,50]; studies on public-space lighting support lighting-related stimuli [39,48,49]; and studies on street activity and urban vitality support activity-related stimuli [46,47]. Together, these five types of visual stimuli constitute the major environmental cues in cold-region winter public spaces that can be perceived, selected, and interpreted by users. However, the interpretation of these stimuli should be understood as context-dependent rather than universal. Their perceptual meanings may vary according to climate severity, snow duration, local winter-maintenance practices, cultural familiarity with ice–snow environments, user demographics, and everyday winter

adaptation behaviors. For example, snow-covered surfaces may be interpreted as scenic or restorative in recreational contexts, but as risky or inconvenient in daily commuting contexts. Similarly, visible winter activity cues may have different meanings for local residents, tourists, older adults, children, and commuters. Therefore, the five-category classification provides an analytical structure for identifying winter visual cues, but its perceptual and behavioral interpretation should be adjusted according to specific climatic, cultural, and user contexts.

Surface-related visual stimuli include snow cover, ice surfaces, high-brightness ground surfaces, pavement boundaries, and path traces. Snow cover and ice can change ground brightness, reflection, material perception, and boundary visibility, thereby affecting pedestrians' judgments of safe paths, obstacles, icy areas, and walkable ranges [44–46,49,55]. Therefore, surface-related stimuli are primarily associated with spatial legibility, perceived walking safety, and willingness to enter.

Vegetation-related visual stimuli include evergreen plants, deciduous trees, exposed branches, seasonal greenery, and winter plant colors. Compared with summer, winter vegetation in cold-region public spaces often shows reduced greenery, lower color diversity, exposed branch structures, and weakened landscape layering, which may influence the area's perceived naturalness, richness, and restorative potential [48,56]. Accordingly, vegetation-related stimuli are important for maintaining winter landscape attractiveness, spatial recognizability, and willingness to stay.

Building interface-related visual stimuli include building façades, street-wall continuity, ground-floor interfaces, entrance recognizability, canopies, and semi-outdoor spaces. This category refers primarily to relatively stable architectural and spatial boundary elements rather than to the activities that may occur around them. As natural landscape cues and outdoor activities decline in winter, building interfaces become more visually prominent and may influence users' judgments of spatial order, orientation, accessibility, and perceived safety [37]. Therefore, this category directly connects winter visual perception mechanisms with architectural and built-environment design variables.

Lighting-related visual stimuli include low solar altitude, long shadows, contrasting patterns of light and shadow, nighttime lighting, façade lighting, path lighting, warm light sources, and glare control. In cold-region winters, short daylight and longer periods of darkness make lighting conditions especially important for entrance recognition, path continuity, node visibility, and perceived safety [41,52]. Lighting-related stimuli are therefore closely related to nighttime accessibility, risk judgment, and willingness to stay.

Activity-related visual stimuli include visible people, commercial interfaces, winter activity facilities, ice–snow activities, seating, street furniture, and activities at public-building entrances. Because outdoor activities often decrease and become more spatially concentrated in winter, visible activity cues are important signs of accessibility, usability, social safety, and place vitality [48,49]. When users see others staying, socializing, exercising, or participating in winter activities, they may be more likely to judge the space as usable and worth entering.

Based on the above classification, Table 2 summarizes the representative spatial elements, cold-region winter visual changes, and main perceptual implications of the five types of winter visual stimuli, thereby providing a classificatory basis for the subsequent interpretation of eye-tracking indicators and design translation.

Table 2. Classification of winter visual stimuli and their perceptual implications.

Visual Stimulus Type	Representative Spatial Elements	Winter-Specific Visual Changes	Main Perceptual Implications
Surface-related stimuli	Snow cover; ice surface; high-brightness ground; pavement boundaries; path traces	Increased brightness; stronger reflection; blurred boundaries; weakened material contrast	Path legibility; perceived walking safety; risk judgment; willingness to enter
Vegetation-related stimuli	Evergreen plants; deciduous trees; exposed branches; seasonal greenery; winter plant colors	Reduced greenery; lower color diversity; exposed branch structures; weakened landscape layers	Naturalness; attractiveness; restorative perception; willingness to stay
Building interface-related stimuli	Building façades; street walls; ground-floor interfaces; entrances; canopies; semi-outdoor spaces	Increased visual dominance of building interfaces; stronger need for entrance and boundary recognition	Spatial order; enclosure; perceived accessibility; place recognition; safety judgment
Lighting-related stimuli	Low solar altitude; long shadows; path lighting; façade lighting; entrance lighting; glare control	Shorter daylight; stronger light–shadow contrast; greater dependence on artificial lighting	Visibility; orientation; perceived safety; nighttime stay intention
Activity-related stimuli	Visible people; commercial interfaces; winter facilities; ice–snow activities; seating; street furniture	Reduced outdoor population; more concentrated activity nodes; higher salience of winter facilities	Vitality perception; social safety; willingness to stay; activity participation

3.2. Eye-Tracking Indicators and Visual Attention Processes

Winter visual stimuli can be transformed into spatial evaluation and behavioral choice only after they pass through visual search, attention allocation, and information processing. Eye-tracking indicators can record gaze fixations, gaze shifts, revisits, saccade paths, and attention distribution across areas of interest, thereby providing processual evidence for explaining how people see winter public spaces [27,47]. In this article, these indicators are not treated as direct evidence of preference or behavior. Rather, they are positioned as mediating indicators that help reveal how winter visual stimuli are attended to, selected, and interpreted before emotional perception, spatial judgment, and behavioral intention are formed.

The interpretation of eye-tracking indicators in cold-region winter environments should be cautious because the same indicator may imply different perceptual meanings. Longer fixations or repeated revisits may indicate attractiveness, but they may also reflect route uncertainty, safety judgment, or cognitive load [57]. Time to first fixation, saccade paths, AOI analysis, and heat maps can help identify which winter cues are detected early, which areas require a repeated visual search, and which design elements are overlooked [34,35,58]. Physiological indicators such as pupil diameter and blinking are particularly sensitive to illumination, glare, snow reflection, low daylight, shadows, and artificial lighting, and therefore, should not be used as independent evidence of emotion unless environmental lighting conditions are carefully controlled [59].

Accordingly, eye-tracking indicators should be combined with subjective evaluation, behavioral observation, thermal-environment data, acoustic evaluation, and spatial morphology analysis. Table 3 summarizes the general meanings, winter-specific interpretations, and methodological cautions of selected eye-tracking indicators.

Table 3. Eye-tracking indicators, winter-specific interpretation, and methodological cautions.

Eye-Tracking Indicator	General Meaning	Winter-Specific Interpretation	Methodological Caution
Fixation duration	Attention intensity; cognitive load	Longer fixation on snow-covered paths, icy areas, blurred boundaries, or entrances may indicate increased need for route judgment, risk recognition, or accessibility assessment	Long fixation may also reflect attraction or uncertainty; it should be interpreted together with safety perception and route-choice data
Fixation count	Repeated attention; visual salience	More frequent fixations on path edges, entrances, lighting nodes, or activity cues may reflect winter-specific dependence on visual guidance	A high fixation count may indicate importance, ambiguity, or visual disturbance
Time to first fixation	Early visual salience; detectability	Delayed first fixation on entrances, hazards, or activity nodes may indicate reduced detectability under low light, shadow, glare, or snow-covered conditions	Strong contrast or lighting may shorten fixation time without necessarily improving overall usability
Saccade path	Visual search; spatial reading	More dispersed saccades may occur when snow cover weakens boundaries, long shadows complicate orientation, or visual cues are insufficient	Saccade patterns should be interpreted together with spatial layout complexity and task type
Area of Interest (AOI)	Attention allocation to predefined elements	Increased AOI share on façades, lighting, entrances, or activity nodes may indicate attention redistribution when vegetation, color, and activity cues decline in winter	AOI definition strongly affects results and should be standardized across seasonal comparisons
Heat map	Spatial distribution of visual focus	Concentrated heat on lighting nodes, path boundaries, or activity nodes may reveal winter focal points; low-attention areas may indicate visually neglected or underused spaces	Heat maps show attention distribution but do not directly indicate positive or negative perception
Pupil diameter	Arousal; cognitive load	Snow reflection, glare, low daylight, and artificial lighting may strongly affect pupil response in winter environments	Pupil diameter should not be used as an independent indicator of emotion unless illumination is controlled

3.3. Eye-Tracking-Testable Propositions for Winter Visual Perception

Building on the classification of winter visual stimuli and the interpretation of eye-tracking indicators, this article formulates five propositions for future empirical validation. These propositions do not represent confirmed empirical findings because this study does not include primary behavioral, physiological, or experimental data. Rather, they specify how the proposed framework can be examined in future studies through VR eye-tracking experiments, mobile eye-tracking in real winter settings, comparative seasonal studies, behavioral observation, subjective evaluation, and environmental measurements.

P1. Surface-related stimuli and risk-oriented attention: With snow cover, icy surfaces, and weakened pavement boundaries, users are expected to show longer fixations, more frequent revisits, and greater attention to path boundaries, icy areas, and wayfinding cues, reflecting increased demand for risk recognition and route judgment.

P2. Lighting-related stimuli and early spatial recognition: Under low solar altitude, long shadows, short daylight, or insufficient nighttime lighting, entrances, path nodes, obstacles, and lighting facilities may show delayed detection and more dispersed visual searching, indicating reduced visual legibility and spatial recognizability.

P3. Vegetation decline and attention redistribution: In winter scenes with reduced greenery, lower color diversity, and exposed branch structures, visual attention may shift from vegetation-related elements toward building interfaces, lighting nodes, and activity cues, as reflected by AOI-based attention share and heat-map concentration.

P4. Activity cues and stay-oriented attention: Visible people, winter facilities, commercial interfaces, seating, and ice–snow activity nodes may attract earlier and more concentrated visual attention, thereby strengthening perceived vitality, social safety, and willingness to stay.

P5. Building interfaces and spatial orientation: When natural landscape cues are weakened in winter, building façades, ground-floor interfaces, canopies, entrances, and semi-outdoor spaces may receive increased fixation and revisiting behavior, reflecting their greater role in orientation, accessibility judgment, and place recognition.

These propositions shift the framework from general conceptual explanation toward an eye-tracking-testable research agenda and clarify which links among visual stimulus, observable attention allocation, inferred perceptual evaluation, and behavioral intention should be prioritized in future empirical studies.

For future empirical validation, these propositions should be operationalized through a combination of eye-tracking indicators, subjective evaluation, behavioral observation, and environmental measurements. Risk perception in P1 can be examined through fixation duration, fixation count, revisit frequency, and AOI attention share on icy surfaces, snow-covered edges, blurred path boundaries, or warning signs, together with perceived safety ratings, route-choice errors, hesitation points, or detour behavior. Spatial legibility in P2 and P5 can be examined through time to first fixation on entrances, path nodes, façades, lighting nodes, and wayfinding cues, together with saccade dispersion, search duration, wayfinding accuracy, and user-rated legibility. Attention redistribution in P3 can be examined by comparing AOI attention shares and heat-map concentration across vegetation, building interfaces, lighting nodes, and activity cues in snowy and non-snowy scenes. Willingness to stay in P4 can be examined through fixation share and revisit frequency based on the number of visible people, available seating, winter facilities, and activity nodes, together with willingness-to-stay ratings, observed stay duration, and activity participation. In this way, the propositions are not treated as direct conclusions from eye-tracking data, but as testable relationships that require coordinated measurement of attention patterns, perceptual evaluations, and behavioral indicators.

3.4. From Visual Attention to Inferred Spatial Interpretation and Behavioral Intention

Visual attention is treated in this article as an intermediate process between winter visual stimuli and inferred spatial interpretation or behavioral intention. Winter visual stimuli constitute visible environmental cues in cold-region public spaces, while eye-tracking indicators can record how users allocate attention to these cues. However, attention data alone cannot confirm emotional states, spatial judgments, or actual behavioral choices. Therefore, this framework does not present a simple linear relationship between visual stimuli and perception and behavior. Instead, it proposes a testable mechanism in which visual attention first filters spatial information and may then contribute to users' interpretation of an area's safety, legibility, attractiveness, and possible action.

Visual attention may first contribute to users' interpretation of perceived safety and spatial legibility in winter public spaces. When ground-surface boundaries, path directions, entrance locations, and lighting nodes are quickly recognized, users may be more likely to interpret the space as clear, identifiable, and potentially accessible. Conversely, when snow cover weakens path boundaries, long shadows create directional uncertainty, or insufficient nighttime lighting makes nodes difficult to identify, attention may be directed

toward possible risks or ambiguous spatial cues. In such cases, eye-tracking evidence would indicate where visual uncertainty occurs, but it would still need to be interpreted together with subjective safety ratings, route-choice observation, and environmental measurements [36,37,41].

Beyond safety and legibility, visual attention may also support users' interpretation of spatial attractiveness, comfort, and restorative potential. Evergreen plants, warm-colored building interfaces, clear activity nodes, and visible human activities may become positive visual focal points within the winter scene. However, whether these focal points actually improve perceived attractiveness or willingness to stay should be tested through combined methods rather than inferred from gaze behavior alone. Similarly, attention to icy surfaces, shadowed areas, enclosed interfaces, empty spaces, or poorly lit areas may indicate possible risk recognition or uncertainty, but actual avoidance, shortened stays, and route changes require behavioral observation for confirmation. Accordingly, the framework treats behavioral choice as a downstream construct that may be informed by visual attention, perceptual evaluation, and action expectations, rather than as an outcome directly determined by gaze behavior.

Based on the above analysis, this article proposes an integrated conceptual framework of winter visual perception mechanisms in outdoor public spaces of cold-region cities. Figure 4 presents the hypothesized links among winter environmental constraints, five types of visual stimuli, observable visual attention, inferred perceptual or behavioral constructs, and design response. These links should be understood as theoretically derived relationships that require future validation rather than empirically confirmed causal pathways. The related stimulus classification and eye-tracking interpretation are further summarized in Tables 2 and 3.

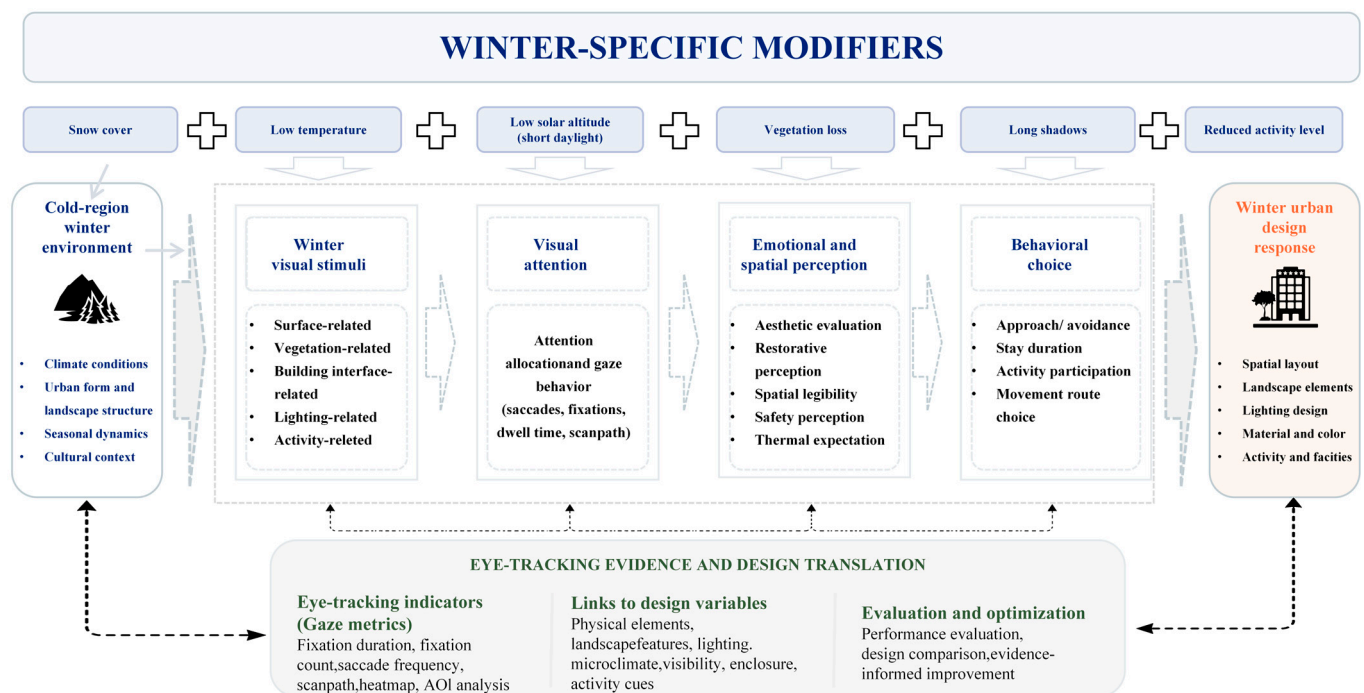


Figure 4. Integrated conceptual framework of winter visual perception mechanisms.

4. Translation into Built-Environment Design and Planning Applications

The conceptual framework proposed in this article can be further translated into built-environment variables for future evaluation and design diagnosis. This translation is not intended to expand the scope of the article from mechanism explanation to a comprehensive design guideline, nor is it presented as an independent contribution separate from the

conceptual framework. Rather, it identifies spatial variables through which the proposed visual-attention mechanism may be observed, compared, and empirically tested in cold-region winter public spaces.

In built-environment research, building façades, ground-floor interfaces, public-building entrances, canopies, semi-outdoor transition spaces, path boundaries, lighting systems, vegetation configuration, and activity nodes are relevant variables because they may operate as visible cues that structure attention allocation, entrance recognition, perceived accessibility, nighttime safety, and the interpretation of possible activities. Therefore, the translation in this section should be understood as an evaluation-oriented and diagnostic extension of the conceptual framework rather than as an independent design prescription. The purpose is not to state what designers should do in all winter public spaces, but to clarify which built-environment variables may be examined when testing the proposed visual-attention mechanism.

4.1. Translating Visual Mechanisms into Built-Environment Design Variables

Winter visual perception mechanisms can be translated into operable architectural and planning content through the correspondence between “visual stimuli–perceptual functions–eye-tracking evidence–built-environment design variables.” Design translation requires understanding the perceptual function of each visual stimulus, identifying the possible evidence of visual attention it may generate, and translating it into corresponding built-environment variables. In other words, snow cover and ground surfaces with high levels of brightness do not merely correspond to “snow removal” or “pavement replacement”; rather, they are related to path-boundary recognition, glare control, perceived safety, and judgments of walkable areas. Similarly, building interfaces are not only objects of façade beautification, but are also associated with entrance recognizability, street enclosure, ground-floor interface openness, semi-outdoor transition, and willingness to stay in winter [37].

Specifically, surface-related stimuli may be examined through variables such as path clarity, anti-slip paving, snow-cleared routes, visibility, low-level signage, and glare control conditions, which are relevant to evaluating path legibility and perceived walking safety in winter spaces. Vegetation-related stimuli may be examined through variables such as evergreen visibility, ornamental branch structure, winter color contrast, and snow-scene focal views, which are relevant to evaluating winter naturalness, visual attractiveness, and restorative potential. Building interface-related stimuli may be examined through variables such as façade order, entrance recognizability, ground-floor interface openness, street-wall continuity, canopies, and semi-outdoor staying nodes, which are relevant to evaluating spatial order, orientation, accessibility, and possible stayability. Lighting-related stimuli may be examined through variables such as path lighting, entrance lighting, node lighting, façade lighting, light color, shadow control, and glare control, which are relevant to evaluating nighttime visibility and perceived safety. Activity-related stimuli can be translated into variables such as winter street furniture, visible activity facilities, active ground-floor commercial interfaces, ice–snow activity nodes, and wind-sheltered sunny staying spaces, in order to strengthen the vitality of places and the possibility of behavioral participation [41,45,46,48–50,52,55,56].

This translation is not a simple listing of design measures, but a transformation of perceptual mechanisms into built-environment variables that can be regulated through architectural design, urban design, and planning evaluation. To make the framework more useful for practitioners, these variables should also be connected with observable design strategies and measurable evaluation indicators. Because this article is conceptual, the indicators proposed here are not presented as fixed performance thresholds. Rather, they

provide diagnostic directions that can be further tested through eye-tracking experiments, field observation, user evaluation, environmental measurement, and post-occupancy assessment. Table 4 therefore summarizes how possible eye-tracking evidence associated with the five types of winter visual stimuli can be translated into built-environment design variables, thereby providing a more specific basis for design diagnosis and planning evaluation.

Table 4. Evaluation-oriented translation from eye-tracking evidence to built-environment variables.

Visual Stimulus Type	Possible Eye-Tracking Evidence	Built-Environment Design Strategies	Measurable Indicators/Evaluation Focus
Surface-related stimuli	Fixations and revisits on path boundaries, icy areas, snow-covered edges, and signage; repeated saccades at path nodes	Strengthen pavement contrast; clarify snow-clearing routes; reinforce path edges; use anti-slip materials; provide low-level signage and node lighting; reduce glare from snow or reflective surfaces	Continuity of cleared walking routes; visibility of path boundaries; contrast between walkway and snow-covered areas; number and visibility of warning signs; fixation/revisit share on path edges and risk areas; route-choice errors or detours
Vegetation-related stimuli	Fixations on evergreen plants, branch structures, winter colors, and snow-vegetation focal points	Increase evergreen planting; use ornamental branches and winter-color plants; create snow-vegetation focal views; maintain layered planting structure; frame winter landscape views	Proportion of evergreen or winter-visible vegetation; visibility of landscape focal points; seasonal color contrast; fixation share on vegetation AOs; user-rated attractiveness, naturalness, or restorative potential
Building interface-related stimuli	Fixations and revisits on entrances, ground-floor interfaces, windows, canopies, and semi-outdoor spaces	Improve entrance visibility; organize façade rhythm and order; activate ground-floor interfaces; provide transparent or semi-open edges; add canopies and semi-outdoor stay spaces; use warm or low-reflective materials	Entrance detection time; visibility distance of entrances; active frontage length or ratio; façade transparency or openness; fixation/revisit share on entrances and interfaces; user-rated accessibility, enclosure, and place recognition
Lighting-related stimuli	Fixations or revisits on lighting nodes, entrance lighting, dark edges, and path brightness changes	Provide continuous path lighting; emphasize entrance and node lighting; use warm light sources where appropriate; reduce glare; improve shadow control; coordinate façade and ground-level lighting	Illuminance level and uniformity; luminance contrast at paths and entrances; glare risk; percentage of dark edges or poorly lit segments; time to first fixation on entrances or obstacles; perceived nighttime safety
Activity-related stimuli	Fixations on visible people, facilities, seating, commercial interfaces, and ice-snow activity nodes	Provide visible winter activity facilities; arrange seating in sunlit or wind-sheltered locations; strengthen active ground-floor interfaces; create visible gathering nodes; support ice-snow activities and public-building entrance activities	Number and visibility of activity nodes; seating availability and visibility; observed user density; stay duration; activity participation rate; fixation share on people, seating, or activity facilities; user-rated vitality and willingness to stay

4.2. Scenario-Based Application of Winter Visual Stimuli

The design and planning translation of winter visual perception mechanisms in different types of public spaces in cold-region cities should reflect differences in spatial scenarios, built-environment characteristics, and user groups. Visual stimuli vary across different spaces, and users' behavioral needs and perceptual priorities also differ. Therefore, the framework proposed in this article should not be understood as a unified design checklist applicable to all spaces, but should instead be applied in a differentiated manner according to specific scenarios, such as winter streets, parks and squares, community outdoor spaces, and urban renewal areas.

Winter streets should prioritize path legibility, building-interface order, lighting continuity, and pedestrian safety. Snow cover, icy ground, wind exposure, and reduced nighttime visibility can affect walking experience and route choice [40]. Therefore, surface-

related, building interface-related, and lighting-related stimuli should be translated into continuous snow-clearing routes, pavement-boundary contrast, wayfinding systems, street lighting, open ground-floor interfaces, entrance recognition, and semi-outdoor wind-sheltered spaces.

Parks and squares should prioritize providing focal points in winter landscapes, activity nodes, wind-sheltered and sunlit staying spaces, and restorative experiences. Winter vegetation decline, reduced outdoor activities, and spatial emptiness can weaken attractiveness and stayability [19,20]. Therefore, vegetation-related, activity-related, and lighting-related stimuli should be translated into evergreen planting, winter colors, snow-scene focal views, ice-snow activity areas, visible staying nodes, children's activity spaces, and sunlit seating.

Community outdoor spaces should prioritize everyday accessibility, vulnerable-group use, entrance recognition, and semi-outdoor staying nodes. Because community spaces are closely connected with daily life, older adults, children, and caregivers are especially sensitive to safe paths, nighttime lighting, and recognizable activity nodes [42]. Therefore, surface-related, building interface-related, lighting-related, and activity-related stimuli should be translated into continuous daily routes, recognizable residential and public-building entrances, safe lighting, children's activity points, elderly resting spaces, and neighborhood interaction nodes.

Urban renewal areas should prioritize visual order, historical interface recognition, ground-floor vitality, and nighttime safety. In cold-region cities, older commercial streets, historic districts, and aging residential areas often face unclear spatial order, inactive interfaces, insufficient lighting, and declining winter vitality. Therefore, building interface-related, activity-related, and lighting-related stimuli should be translated into improvements in façade, entrance recognition, ground-floor functional renewal, street-wall continuity, semi-outdoor staying spaces, winter lighting, and supplementary activity facilities [54]. To further clarify how the proposed framework can be applied across different types of cold-region public spaces, Figure 5 presents a scenario-based design translation and evaluation pathway. It highlights the priority visual stimuli, main design concerns, and possible evaluation approaches for winter streets, parks and squares, community outdoor spaces, and urban renewal areas. Table 5 complements this figure by summarizing the corresponding application scenarios, priority visual stimuli, main design concerns, and evaluation feasibility. By distinguishing between basic and advanced evaluation methods, the table also responds to the practical differences between planning-oriented assessment and future empirical validation.

Table 5. Scenario-based applications and evaluation feasibility in cold-region cities.

Application Scenario	Priority Visual Stimuli	Main Design Concerns	Basic Evaluation Methods	Advanced Evaluation Methods
Winter streets	Surface; building interface; lighting	Path legibility; walking safety; orientation; nighttime visibility	Field observation; user survey; lighting audit; winter walking-route mapping	Mobile eye-tracking; GPS-based route tracking; luminance and glare measurement
Parks and squares	Vegetation; activity; lighting	Attractiveness; restoration; vitality; stayability	Preference survey; behavior mapping; seasonal photo comparison; facility-use observation	VR eye-tracking; multisensory experiment; visual-thermal comfort comparison

Table 5. Cont.

Application Scenario	Priority Visual Stimuli	Main Design Concerns	Basic Evaluation Methods	Advanced Evaluation Methods
Community outdoor spaces	Surface; building interface; lighting; activity	Daily accessibility; safety; vulnerable-group use; neighborhood interaction	Resident survey; seasonal observation; participatory mapping; post-occupancy evaluation	Mobile eye-tracking with older adults or children; wearable thermal-sensation recording; longitudinal behavior tracking
Urban renewal areas	Building interface; activity; lighting	Place recognition; visual order; ground-floor vitality; perceived safety	Street-view audit; nighttime safety survey; post-occupancy evaluation; façade-interface checklist	Eye-tracking experiment; street-view image analysis; computer-vision-based façade and lighting assessment

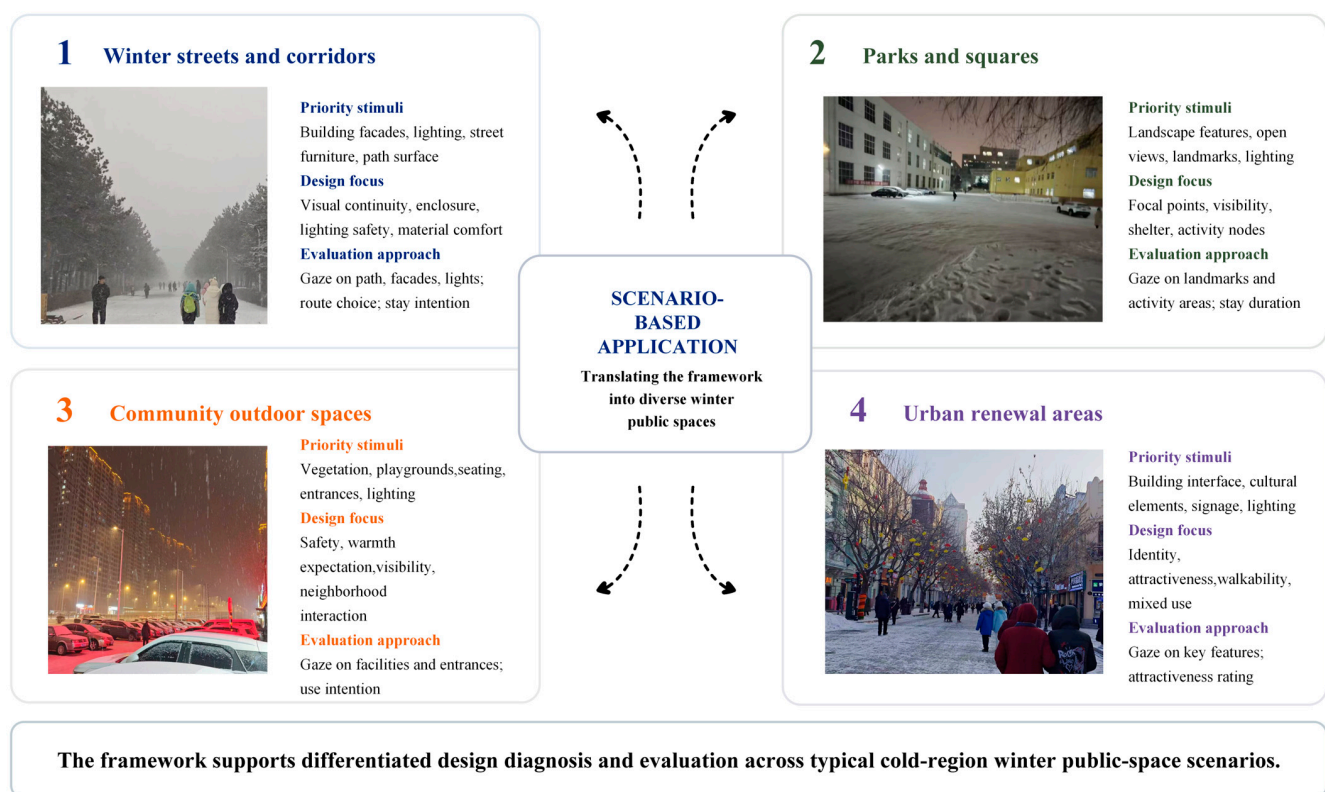


Figure 5. Scenario-based design translation and evaluation pathway.

4.3. Integrating Visual-Attention Evaluation into Winter Design Processes

After translating visual mechanisms into design variables and application scenarios, a further question to consider is how eye-tracking indicators and future eye-tracking-based evidence can be incorporated into planning evaluation systems. Traditional evaluations of cold-region public spaces usually emphasize meteorological monitoring, thermal-comfort indices, spatial morphology analysis, subjective satisfaction, and behavioral observation. These methods can explain whether a space is cold, safe, and basically usable, but they are less able to reveal which spatial elements users actually notice, which elements are overlooked, and which cues cause recognition difficulty or cognitive load [27,47].

For practical application, designers can use the proposed framework as a staged evaluation process during winter design. First, in the site-diagnosis stage, winter visual stimuli can be identified through field observation, winter photo records, street-view images, snow-clearing route mapping, lighting audits, and behavior mapping. Second, in

the design-testing stage, alternative design schemes can be represented through winter renderings, street-view simulations, or VR scenes, and key areas of interest can be defined around entrances, path boundaries, façades, lighting nodes, vegetation focal points, seating areas, and activity nodes. Third, in the evaluation stage, visual attention can be assessed using indicators such as time to first fixation, fixation duration, fixation count, revisit frequency, AOI attention share, heat-map concentration, and route-choice records. Emotional and perceptual responses should not be inferred from eye-tracking data alone; rather, they should be evaluated through complementary measures such as perceived safety, attractiveness, warmth expectation, spatial legibility, restoration, comfort, and willingness-to-stay ratings. Finally, in the design-revision stage, mismatches between intended design cues and observed attention or perception can be used to adjust entrance visibility, path guidance, lighting continuity, façade-interface treatment, vegetation composition, and activity-node placement.

Future evaluation can therefore combine eye-tracking indicators with subjective evaluation, behavioral observation, thermal-environment data, acoustic evaluation, and spatial morphology analysis. VR eye-tracking can be used during the design stage to compare alternative façade, lighting, vegetation, path-boundary, and activity-node schemes under controlled winter scenes. Mobile eye-tracking can be used after construction or during post-occupancy evaluation to record gaze behavior, route choice, hesitation points, and staying patterns in real winter streets, parks, and community spaces [60,61]. Street-view images and computer vision methods can further support the extraction of building interfaces, green views, sky views, lighting nodes, and activity cues. Subjective evaluation should be designed to capture emotional and perceptual responses that eye-tracking cannot directly measure, including perceived safety, visual comfort, attractiveness, restorative potential, expectation of warmth, vitality of a place, and willingness to enter or stay.

Eye-tracking indicators do not replace traditional planning evaluation methods. Rather, they provide supplementary evidence for the visual attention process. For example, if a thermally acceptable space is still difficult to read visually, or if activity facilities fail to become visual focal points, this may indicate problems of legibility, guidance, or spatial arrangement [62]. When combined with the measurable indicators summarized in Table 4, such as entrance detection time, fixation share on risk areas, visibility of path boundaries, lighting uniformity, stay duration, and user-rated safety or attractiveness, planning evaluation can move from asking “whether spatial conditions meet standards” to asking “whether the space is effectively perceived and usable in winter.”

5. Discussion

Based on cross-disciplinary literature integration and conceptual synthesis, this article constructs a conceptually derived and eye-tracking-testable framework for visual perception mechanisms in winter outdoor public spaces of cold-region cities. Because the study does not include empirical testing, the framework should be interpreted as a theoretical outcome and a future validation agenda rather than as providing evidence of confirmed relationships. The discussion therefore focuses on the theoretical assumptions, design implications, boundary conditions, research limitations, and empirical validation needs of the proposed framework. In particular, relationships among winter visual stimuli, observable visual attention, inferred spatial interpretation, behavioral intention, and design response are discussed as hypothesized links that require future empirical examination.

5.1. Theoretical Contribution and Application-Oriented Implications

First, this article conceptually reframes cold-region winter public spaces as seasonal perceptual environments rather than only as objects of thermal comfort and microclimate

optimization. This reframing shifts attention from whether spaces are physically usable to how they may be visually perceived, interpreted, and potentially chosen under winter conditions. It provides a broader theoretical perspective for the proposed framework by emphasizing that the usability of winter public spaces is shaped not only by physical environmental performance, but also by how users visually recognize and interpret seasonal spatial cues.

Second, the article proposes a winter-specific visual-attention mechanism as its primary theoretical contribution. This mechanism links seasonal visual stimuli with observable attention processes and inferred perceptual or behavioral constructs. It does not replace thermal, microclimatic, or acoustic explanations; rather, it adds an intermediate explanatory layer between winter environmental conditions and public-space use. More specifically, it explains how visible winter cues may be noticed, filtered, and cognitively organized before users form judgments of safety, legibility, attractiveness, comfort, vitality, or behavioral intention.

Third, the article translates this mechanism into built-environment variables for future evaluation and design diagnosis. This design translation should be distinguished from the primary theoretical contribution. It is not presented as an independent theoretical framework or as a universal design guideline. Rather, building façades, ground-floor interfaces, entrances, canopies, semi-outdoor spaces, path boundaries, lighting systems, vegetation configuration, and activity nodes are treated as application-oriented variables through which the proposed visual-attention mechanism may be evaluated, diagnosed, and empirically tested. In this sense, theoretical advancement and applied implications are related but not equivalent: the former provides the explanatory framework, while the latter provides possible pathways for future testing and practical application.

5.2. Visual–Thermal–Acoustic Interactions and Winter Specificity

Although the framework focuses on visual perception mechanisms, winter public-space experience is inherently multisensory. Thermal comfort remains a fundamental condition for outdoor use, but it is also anticipated and interpreted through visible spatial cues such as sunlight, shade, snow-cleared paths, wind-sheltered corners, seating exposure, building interfaces, and visible human activity. Thus, visual perception may shape users' expectations of warmth, safety, and usability before direct bodily experience is fully formed.

Visual and thermal perception may interact in three ways. Visual cues may amplify or weaken perceived thermal comfort, guide users toward thermally favorable micro-locations, and reduce willingness to stay when glare, excessive contrast, or unclear boundaries create visual discomfort. Acoustic perception may also be shaped by visible activity cues. In winter, reduced vegetation, fewer outdoor activities, and snow-covered ground can change both the sound environment and the interpretation of sound sources. The visibility of people, commercial interfaces, and winter activities may make sounds more socially meaningful, whereas visually empty spaces may make similar sound levels feel uncertain or less inviting.

These interactions clarify the boundary of the proposed framework. The framework does not claim that visual perception is more important than thermal comfort in all winter contexts, nor does it aim to explain all multisensory processes in winter public spaces. Instead, it focuses on how visible winter cues may provide early information for users' interpretation of warmth, safety, accessibility, and social presence. Whether such interpretations lead to entering, staying, avoidance, or revisiting should be examined through future empirical studies that combine eye-tracking data, thermal-environment measurements, acoustic evaluation, subjective perception, and behavioral observation.

5.3. Limitations and Future Empirical Validation

As a conceptual article, this study develops the proposed framework through literature integration and conceptual synthesis, but it does not include primary empirical data, behavioral observation, physiological measurements, or experimental validation. Therefore, the proposed relationships between winter visual stimuli, visual attention, perceptual evaluation, behavioral intention, and outdoor-space use should be understood as theoretically derived and testable rather than empirically confirmed. This limitation restricts the ability of the present article to determine causal relationships, effect strengths, or the relative importance of different visual stimuli. Future research should therefore move from conceptual explanation to empirical validation. Three directions are particularly important.

First, future studies should conduct seasonal comparison experiments to test whether snowy and non-snowy scenes produce different visual attention patterns, perceptual evaluations, and behavioral intentions. Such studies could compare different snow-cover levels, vegetation configurations, lighting conditions, building interface designs, and activity cues in controlled VR environments or real winter settings.

Second, future studies should test the eye-tracking propositions proposed in this article by combining fixation, saccade, AOI, heat-map, and pupil-response indicators with subjective evaluation, behavioral observation, route-choice tracking, stay-duration measurements, and physiological or environmental monitoring. This can help clarify whether surface-related, vegetation-related, building interface-related, lighting-related, and activity-related stimuli produce expected attention patterns and whether these attention patterns are associated with perceived safety, spatial legibility, emotional evaluation, behavioral intention, or actual outdoor-space use.

Third, future studies should consider contextual differences in the interpretation of winter visual stimuli. These differences may include cultural background, climate severity, snow-cover duration, local maintenance practices, user demographics, and winter adaptation behaviors. Older adults, children, commuters, tourists, and local residents may differ in visual search strategies, risk perception, thermal sensitivity, familiarity with snow and ice, and activity needs. Cross-cultural and cross-climatic comparisons with cold-region areas such as Northern Europe, Canada, Northeast China, and Hokkaido, Japan, could further test the applicability of the framework under different winter urban cultures, climatic conditions, and built-environment conditions.

6. Conclusions

This article demonstrates the development of a conceptually derived and eye-tracking-testable framework for understanding winter visual perception mechanisms in outdoor public spaces of cold-region cities. As a framework outcome rather than an empirical result, the proposed model links winter environmental constraints, seasonal visual stimuli, observable visual attention, and inferred perceptual or behavioral constructs. It extends cold-region public-space research beyond a thermal-comfort-oriented explanation while maintaining a focused analytical boundary. However, the framework should be understood as hypothetical until it is validated through empirical studies.

The main contribution of this article is not to replace thermal-comfort or microclimate research, nor to provide a comprehensive or empirically confirmed model of winter public-space experience. Rather, it proposes a theoretically grounded explanation of how winter-specific visual conditions may organize visual attention and how this attention process may inform subsequent interpretations of safety, legibility, attractiveness, warmth, social presence, and possible action. Snow reflection, weakened path boundaries, vegetation decline, long shadows, lighting dependence, and reduced outdoor activity are

therefore treated as hypothesized visual cues rather than verified determinants of perception or behavior.

For architectural and built-environment research, the framework provides a basis for translating visual perception mechanisms into operable design and evaluation variables, including building façades, ground-floor interfaces, public-building entrances, canopies, semi-outdoor spaces, path boundaries, lighting systems, vegetation configuration, and winter activity nodes. Its knowledge contribution lies in extending existing seasonal urban design models from climate adaptation, spatial provision, and activity programming toward a more process-oriented understanding of winter public-space usability. Specifically, the framework adds a visual-attention layer that connects seasonal environmental change with users' spatial interpretation and behavioral intention. This translation should be regarded as an evaluation-oriented agenda for future research and design diagnosis, rather than as a validated design guideline.

Future research should move from conceptual explanation to empirical validation. Priority directions include testing the proposed propositions through snowy and non-snowy scene comparisons, VR or mobile eye-tracking experiments, multisensory visual–thermal–acoustic evaluation, behavioral and physiological measurements, and cross-context comparisons among different cold-region cities and user groups. Such work is necessary to determine whether the hypothesized relationships among winter visual stimuli, attention allocation, perceptual evaluation, behavioral intention, and outdoor-space use are supported by empirical evidence.

Author Contributions: Conceptualization, J.Z.; methodology, J.Z.; software, J.Z.; validation, J.Z.; formal analysis, J.Z.; investigation, J.Z.; resources, X.G.; data curation, J.Z.; writing—original draft preparation, J.Z.; writing—review and editing, J.Z.; visualization, J.Z.; supervision, X.G.; project administration, X.G.; funding acquisition, X.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Postgraduate Research & Practice Innovation Program of Jiangsu Province, grant number SJCX25_1825.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: We thank all participants for their time and cooperation.

Conflicts of Interest: The authors declare no conflicts of interest.

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