

A Study on the Evaluation of Classroom Environmental Comfort in Colleges and Universities from the Perspective of Human Factors Engineering

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Abstract: The environmental comfort in university classrooms affects learners' cognitive efficiency and physical/mental state however most evaluations are restricted by comparing single physical parameter threshold without considering the mechanisms of human factors. From the perspective of human factors engineering this research includes three aspects such as theoretical construction, model design and mechanism analysis. Based on the integration of sensory thresholds, cognitive load and environmental stress theories, we established a progressive analytical framework and analyzed the interactive coupling characteristics between four types of environmental factors; developed a three-level tree-structured evaluation index system and a fuzzy preference weight aggregation strategy which can be used to construct a comprehensive evaluation mechanism that integrates both objective data-driven and subjective correction; Analyzing the pathway of factor transmissions via the stimulus-organism-response paradigm revealed the dynamic shaping effect of climate adaptation and behavior patterns on comfort needs so as to provide systematic theoretical tools and methodological supports for evaluating university classroom environment.

Keywords: Human Factors Engineering; University Classrooms; Environmental Comfort; Evaluation Model; Influencing Mechanism; Dynamic Adaptability

Introduction

The quality of classroom environments in universities influences learners' cognition performance and their physical/mental health over time but most of the evaluations conform to general standard for building environment and ignore the context-specific characteristics such as high cognitive load, long exposure period, high density crowd of learning activities; they mainly adopt single physical measurement or satisfaction survey without an integrated framework of objective parameter and subjective experience. Based on the viewpoint of human factors engineering, by taking the laws of human information processing and multisensory integration as the starting point, we develop a systematic evaluation framework that includes an index system, subjective weight assignment and an integrated comprehensive evaluation mechanism, which deeply analyzes the action path of environmental factors and dynamic evolution laws of comfort needs aiming at providing theoretical support for methodological innovation in this field.

1. Theoretical Construction and Multidimensional Analysis of Environmental Comfort in University Classrooms

1.1 Theoretical Foundations of Comfort Perception in Human Factors Engineering

Research on human factors engineering for comfort perception is intended to study how physical environment parameters transform into subjective experience through human physiological sensory channel. Sensory threshold theory describes such a transformation process; it claims that external stimuli will lead to conscious perceptual judgment affecting comfort evaluation if crossing the individual's absolute sensory threshold and differential sensory threshold. Usually dynamic physical quantities (temperature change rate, illumination gradient, or sudden noise peak), which exist in classroom has a typical S-shaped psychophysical function relationship between its intensity with the probability of being perceived so we need to be concerned both with average value and extreme value and rate of change^[1].

Cognitive Load Theory reveals competition between environmental information processing and learning cognitive tasks -- constant crowded out of limited mental information processing resources caused by highly varying background noise or unstable thermal and humidity conditions in classrooms reduces individual's attention allocation to classroom content and working memory efficiency (the resource crowding-out effect becomes especially obvious when it comes to high-difficulty learning tasks); Environmental Stress Theory describes accumulation of physiological compensatory load resulting from continuous environmental discomfort on a longer time scale; it suggests that continuous activation of the hypothalamic-pituitary-adrenal axis results in chronic fatigue and emotional exhaustion whose impact is not just the sum of momentary discomfort. Three types of theories correspond respectively at the initial end, intermediate processing stage and cumulative end of environmental perception -- forming an analysis chain layering from momentary awareness and cognitive processing to long-term adaptation, providing a multilevel theoretical basis for research into classroom comfort.

1.2 Composition of Multiple Environmental Factors in University Classrooms and Analysis of Their Interaction Effects

The environmental comfort in university classrooms comprises four major aspects: thermal and humid environment, light environment, acoustic environment and air quality which correspond to clear systems of measurable parameters respectively. The thermal and humid environment is composed of air temperature, mean radiant temperature, relative humidity, and air velocity which directly impacts the human body's thermal balance with its overall effect being able to describe as operative temperature; light environment contains illuminance level, illuminance uniformity, and color temperature relating to visual task efficiency and circadian rhythm regulation; acoustic environment contains equivalent continuous A-weighted sound level, speech interference level, and reverberation time affecting the quality of speech information acquisition and the fluency of cognitive processing; indoor air quality reflects the level of respiratory comfort and the adequacy of oxygen supply measured by such parameters like carbon dioxide concentration, inhalable particulate matter, and total volatile organic compounds. Although dividing these into four types of factors makes it easy for their parametric descriptions and measurements, actually they have significant interactive coupling features when applied in actual classrooms.

At high temperatures our subjectivity towards noise interference increases dramatically; an increase in noise level may decrease users' recognition of stuffiness in the air; When with low illuminance, the human body's tolerance window of temperature fluctuation becomes narrow. Above cross modal nonlinear interaction effect is caused by the integrative processing mechanism of multisensory information on the cerebral cortex: Any change of a single factor affects the comprehensive response of other dimensions. There are also interactions among different parameters within the same dimension (for instance, the combination of changes in temperature and humidity determines effective temperature which is a comprehensive thermal comfort index) We should not just think about single dimensional thinking but multidimensional factors forming a unified interactive field.

1.3 Cognitive Dimensions and Measurement Logic of Classroom Environmental Comfort Evaluation

Evaluations of classroom environmental comfort involve users' multilevel subjectivity for environmental quality which are categorized at different cognitive depths (shallow to deep) in three increasingly high levels: first-level physiological acceptability describes an individual tolerance judgment about deviation of physical parameters against the steady-state range that is based on somatosensory feedback from internal homeostasis maintenance mechanisms like thermoregulation and visual regulation (e.g., sweating/shivering/eye muscle fatigue); this is reflected with a bottom-line judgment of tolerating/not tolerating the current environment. Second-level psychological pleasantness describes user's emotional responses and aesthetic preferences towards environmental quality including the degree of subjective preference toward spatial brightness, acoustic comfort and air freshness. It goes beyond basic physiological needs and belongs to affective evaluation. Third-level task support describes the facilitation/inhibition effect of environmental quality on cognitive efficiency under certain learning activities, i.e., does the environment facilitate attention maintenance when doing long-term reading, speech interaction clarity during group discussion, and thinking fluency during complex problem solving? This is the highest level of cognitive judgment related directly to the effectiveness of learning behavior^[2].

There are three levels which gradually increase from low to high. High level of comfort experience is accumulated based upon basic satisfaction at lower levels without any level will weaken the completeness of overall comfort. Realization of strategy design corresponds level by level through measurement logic around this hierarchy cognitive structure: Measurement for physiological acceptability emphasizes the mapping relationship between the degree of physical deviation and the intensity of disturbance that directly links to the degree of physical deviation as linguistic framework; Measurement for psychological pleasantness needs an introduction of evaluation dimensions at the level of affective tendency, adopting design approach of attitude scales to catch user's preference tendencies; While Measurement for task support connects comfort perception with the subjective perception of efficiency in learning behavior, focusing on individual subject assessment of their own concentration and thinking efficiency under different environmental conditions. Organic integration of the three levels in measurement logic constitute a systematic description of the complete cognitive picture of classroom environmental comfort.

2. Construction of an Evaluation Model for Environmental Comfort in University Classrooms and Methodological Design

2.1 Hierarchical Architecture of the Evaluation Index System and Screening Rules for Key Indicators

Designing an evaluation index system for environmental comfort in university classrooms should be theoretically complete yet operationally feasible—we adopt a three-level tree which points its target layer to the comprehensive evaluation value of environmental comfort, divides it into four major criteria (thermal and humid comfort, visual comfort, acoustic comfort, air quality comfort) according to the multidimensionality of the classroom environment, and consists by directly measurable physical parameters under every criterion item.

The three principles are adopted in indicator screening – theoretical relevance, quantifiability, and independence: first principle (theoretical relevance), meaning that selected indicators should be verified by the aforementioned human factors theoretical framework as important environmental variables which affect comfort perception significantly; second principle (quantifiability) indicating that indicators shall have defined operations with standard physical measurement methods; third principle (independence): control the degree of overlapping information between indicators so that there will not be any redundant evaluation due to high correlation. According to these rules, we initially select air temperature, relative humidity, mean radiant temperature, air velocity, illuminance, illuminance uniformity, color temperature, equivalent continuous A-weighted sound level, speech interference level, reverberation time, carbon dioxide concentration, and inhalable particulate matter, then perform correlation analysis to diagnose collinearity problems among indicators, eliminate redundant indicators whose correlation coefficient exceeds a predetermined threshold, forming a streamlined and complete indicator system.

2.2 Weight Assignment Method Based on Subjective Responses and Preference Information Aggregation Strategy

The essence of weight assignment is defining the difference among the contribution of each evaluation indicator towards overall comfort (reflecting the sensitivity of different user groups for environmental factors and their priorities), since the comfort evaluation has a subjective experiential feature, therefore, the source of weight information should not only be objectively derived from physics but also from users' subjective response. We adopt a preference information collection method under a group decision-making environment to collect users' judgment about the pairwise relative importance of indicators; considering that there are some levels of uncertainty and fuzziness when people make judgments, using interval numbers or triangular fuzzy numbers can better truthfully reflect the degree of hesitation and grey cognition existing in evaluators during the comparison process^[3].

Based on it, we design a preference information aggregation strategy which calculate the degree of deviation between each evaluator's judgment matrix and the group mean matrix (eliminate abnormal judgments with too much deviation) to ensure the level of group consensus; then aggregate individuals' fuzzy weights into a group comprehensive weight vector by geometric mean or weighted aggregation method. This aggregation realizes transition from scattered individual preferences to stable group consensus and increase the flexibility of weight coefficients' semantic expression through a fuzzy

information processing mechanism so that the resulting weights reflect both the group and include the uncertainty information inherent in subjective judgments.

2.3 Applicability Comparison and Selection of Comprehensive Evaluation Algorithms and Design of a Fusion Mechanism

The choice of comprehensive evaluation algorithm influences the reliability and discriminating ability of ultimate evaluation value: each algorithm emphasizes in evaluating an object like classroom environmental comfort (physical objectivity plus experiential subjectivity), linear weighted method has easy intuitive calculation, assuming that all indicators are independent from one another; there might be evaluation bias under classroom scenario if there exists obvious interactive coupling effect between environmental factors. The fuzzy comprehensive evaluation method is good for solving mixed problem with qualitative judgment and quantitative data, incorporating fuzziness contained by user's linguistic description into calculation process, however, it heavily depends on artificial setting during designing membership function.

To address the problem where both objective physical measurement data and subjective questionnaire survey data exist when evaluating classroom environment, we propose an algorithmic complementarity-based fusion mechanism which uses objective physical data driving the entropy weight method to get the objective weights according to the degree of data dispersion but subjecting to correction from subjective response weights as comprehensive weights combining both subjective and objective aspects; executing weighted comprehensive method and fuzzy comprehensive evaluation method at the same time in the process of generating evaluation values, finally obtaining the reliable interval of the evaluation value through comparison with the ranking consistency of their output results if there have significant divergence in the evaluation rankings of the two algorithms. If they have significant divergence in the evaluation rankings of the two algorithms, then use the compromise solution ranking logic to coordinate them so that a compromise scheme can be obtained via setting a balance mechanism between maximum group utility and minimum individual regret. The proposed fusion design overcomes the inherent limitation of any one algorithm and enhances the robustness of evaluation result against disturbance in algorithm choice.

3. Influencing Mechanism and Dynamic Evolution Characteristics of Environmental Comfort in University Classrooms

3.1 Structural Analysis of the Action Pathways of Environmental Factors and the Logic of Mediation Effect Testing

The impact of environment on classroom comfort has been found to be indirectly affected because it transforms via a sequence of physiological and psychological mediating variables until it forms the final comfort judgment. We build up a theory model based on the stimulus-organism-response paradigm in which environmental physical parameters were considered as exogenous stimulus variables; individual's physiological arousal level, emotional state and perceived task difficulty were considered as mediating variables and overall comfort evaluation was considered as an endogenous outcome variable. For example, the effect of temperature on comfort can be fully mediated via thermal sensation vote as a physiological mediating variable or that of noise on comfort can have both indirect effects partially mediated via annoyance and partially via the cognitive path of interfering with speech comprehension.^[4]

Essence of mediation effect test lies in decomposing the total effect as a combination of direct and indirect effects, and determining the dominant modes of action of each environmental factor based on magnitude and significance comparison among them. Proportion of the indirect effect mediated by thermal sensation is much greater than that of the direct effect within the total effect of the temperature factor which indicates that the effect of temperature on comfort is dominated by the physiological perception pathway; whereas the indirect effect of lighting might realize at the same time via two parallel mediating paths (visual fatigue and emotional arousal), with difference in effect size reflecting the differentiation response characteristics of different cognitive level towards environmental stimuli. Quantitative breakdown of effect sizes enables us to define the differentiated role and dominant pathways of various environmental elements in forming comfort.

3.2 Adaptive Regulation Mechanisms of Thermal and Humid Environments under Different Climate Conditions

In general, the university classroom has a mixture of natural ventilation and mechanical regulation. The indoor thermal and humid environments change regularly because of the periodic fluctuation of outdoor climate condition; meanwhile, users do narrowing the gap between the real environment and the ideal comfort state through their multilevel adaptive regulation. According to the human thermal adaptation model, there exist three parallel pathways: behavior adjustment, physiological acclimatization, and psychological adaptation. In behavior adjustment, people autonomously operate (e.g. open/close door/windows, add/remove clothes, use fans etc.), which is the most direct and effective regulation method. Physiological acclimatization reflects regional difference on the thermoregulatory system of population who lives long-term in certain climate region with respect to sweating threshold and vasomotor response so as to enable populations long exposed to hot-summer and cold-winter regions to have a higher tolerance range for annual temperature variation.

The origin of psychological adaptation arises by individuals' cognition with respect to their habitual climate condition. Decrease of comfort evaluation occurs when the actual environmental parameter deviates from individuals' psychological expectation value, which will change its evaluation benchmark once it becomes a norm. Different climate conditions lead to significant difference on the activation sequence and weight for each regulation pathway: behavioral adjustment dominate in transitional seasons but physiological acclimatization and psychological adaptation are dominant in the summer cooling period; whereas the winter heating period depends upon the thermal insulation performance of the building envelope and the active adjustment of individual clothing. Very important to analyze such differential regulation pattern so that we can understand the applicable boundary of static thermal comfort indices under dynamic climate conditions^[5].

3.3 Analysis of Differences in Comfort Needs under Usage Time Periods and Learning Behavior Patterns

The demand for classroom environmental comfort differs significantly with switching of usage time periods and learning behavior patterns which is based on temporal change of human physiological rhythms and cognitive activity characteristics. In terms of usage time periods, the human body's core temperature, alertness level and melatonin secretion show regular fluctuation every day (circadian). The individuals during morning period are at an increasing stage of alertness and they clearly prefer higher color temperature in the light environment whereas there is a natural decline in their alertness in the afternoon period corresponding to declining tolerance towards environmental noise and temperature fluctuations. Differences in learning intensities that correspond to different teaching weeks or semester stages will also affect user comfort needs too. During the final examination review period due to the superposition of prolonged continuous sitting and high cognitive load, users become highly sensitive to seat thermal comfort and air quality^[6].

Regarding the learning behavior pattern: Physical activity level of students in lecture-type classroom is relatively low with stable metabolic heat production where the requirement of speech clarity in the acoustic environment outweighs others; There are often multidirectional verbal interactions in seminar type classroom whose masking effect of background noise amplifies, which puts high requirements for the signal-to-noise ratio of the acoustic environment; Visual task dominates in self study behavior, and uniformity of illuminance and illuminance level on the work surface become the most important comfort variable. Differences in behavior pattern essentially change the rank of importance of environmental factors. It implies it's hard to cover diverse usage scenarios in classrooms by a fixed set of evaluation weights, and intelligent environmental regulation strategy needs dynamic adjustment capability to evaluate benchmark based on time period and behavior pattern.

Conclusion

From the perspective of human factors engineering this study systematically researched environmental comfort in university classrooms involving theory construction, model design and mechanism analysis: theoretically integrated sensory threshold, cognitive load and environmental stress theories; clarified the progressive mechanism of transforming physical stimuli into subjective experience via sensory channels and revealed the interactive coupling characteristics among four types of environmental factors and three-level cognitive dimension structure; designed a three-level

tree-structured index system, established a fuzzy preference weight assignment and group aggregation strategy, proposed a comprehensive evaluation algorithm which incorporates both objective data-driven and subjective correction so as to enhance the robustness of evaluation results against algorithmic disturbances; analyzed mechanisms of action pathways of factors based on the stimulus-organism-response paradigm and revealed the climate adaptive regulation laws of the thermal and humid environment and dynamic shaping effect of behavioral patterns on comfort needs. This study holds that classroom comfort is a subjective construction by physical stimuli via multilevel processing, and we need shift our evaluation logic from parameter compliance to supporting judgments about cognition activities and physical and mental states. Future work can be extended towards dynamic tracking, adaptation to individual differences, and an evaluation-regulation closed loop.

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