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RESEARCH ARTICLE

Universal Design-Based Integration of UDET, Spatial Syntax and QCA Methods for Equitable Child-Friendly Environment Planning A Multilevel Decision Framework

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ABSTRACT

Child-friendly environments are increasingly promoted in urban planning, yet many such spaces remain shaped by adult-centered norms and standardized safety principles, limiting their ability to accommodate children's diverse physical, sensory, and developmental needs. Although Universal Design (UD) offers an inclusive theoretical foundation, its practical application in child-oriented environments has often lacked empirical grounding and decision-oriented evaluation tools.

This study explores how UD principles can be operationalized in child-friendly environments through a multilevel, mixed-method framework. Three public children's spaces in Beijing, Shanghai, and Guangzhou were examined using sequential quantitative and qualitative approaches. Quantitative analyses combined Universal Design Evaluation Tools (UDET), spatial syntax indicators, and multilevel linear models to examine relationships between spatial characteristics and children's behavior. Qualitative insights were derived from participatory observation, child-led visual methods, and stakeholder interviews, and were integrated using an explanatory spiral approach. Qualitative Comparative Analysis (QCA) was further applied to identify combinations of design conditions associated with inclusive outcomes.

The findings indicate that physical accessibility, sensory inclusivity, and risk gradation influence children's engagement in distinct but interrelated ways. Spaces that simultaneously supported accessibility and sensory regulation showed substantially higher participation, particularly among children with disabilities and neurodiversity. Spatial configuration also played an important role, with integration, intelligibility, and visual connectivity shaping patterns of engagement and exploration. Rather than relying on single design elements, inclusive child-friendly environments emerged from specific combinations of spatial, sensory, and social conditions.

Based on these results, the study proposes a Child–Environment Fit Index (CEFI) to support evidence-informed planning and design decisions. The framework contributes to a more grounded understanding of how universal design principles can be translated into inclusive, context-sensitive child-friendly environments.

Keywords: Universal Design; Child-Friendly Environments; Inclusive Spatial Planning; Spatial Syntax; Mixed-Methods Research; Qualitative Comparative Analysis

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1. Introduction

1.1. Background and rationale

Child-Friendly Environments (CFE) are an important part of sustainable development, aimed at creating inclusive, safe, and accessible growth spaces for children. The United Nations Children's Fund emphasizes that such environments should safeguard children's rights, provide safe activity spaces, equal opportunities for participation, and facilities that promote physical and mental health [1]. However, many urban spaces currently center around adults and overlook the special needs of groups such as disabled children and children with neurological diversity, leading to their marginalization [2]. Universal Design (UD) was proposed by Ronald L. Mace, initially focusing on accessible environments for people with disabilities. It has now developed into a comprehensive design framework that meets the needs of different ages, abilities, and cultural backgrounds [3]. Due to the physical, cognitive, and behavioral diversity of children, the application of UD principles in CFE is particularly important [4]. With the acceleration of urbanization, there is an urgent need for child-friendly public spaces, schools, and playgrounds [5]. Although some countries have attempted to integrate UD into design, systematic research and practical guidelines are still insufficient, especially in developing countries where resource constraints often result in designs that fail to fully meet the diverse needs of children. The research aims to explore how UD principles can optimize CFE, ensure that all children can grow up in inclusive environments, and provide practical recommendations for urban planners, architects, and educators to promote more inclusive space design.

1.2. Research problem

There are two key limitations to the current research: (1) UD research focuses more on adults and specific disabled groups, neglecting the special needs of children; (2) CFE research focuses on behavioral patterns and security design, lacking systematic integration of diverse needs. This theoretical disconnect often leads to "child-friendly" spaces in practice that fail to truly meet the participation needs of groups such as disabled children and sensory sensitive children. The research aims to bridge this gap and explore how to create a truly inclusive and child-friendly environment through the systematic application of UD principles.

1.3. Research objectives

The research aims to build a theoretical and practical bridge between UD and CFE. (1) To identify key UD principles relevant to CFE. (2) To analyze how UD principles enhance accessibility, safety, and engagement in various child-friendly spaces. (3) To assess the impact of UD-based designs on children's interaction, mobility, and learning experiences. (4) To provide policy recommendations for urban planners, architects, and educators to integrate UD in CFE effectively.

1.4. Research questions

The research focuses on four core questions. (1) How to adjust the UD principle to meet the special needs of children, including balancing age differences and universality; (2) How UD design can reduce participation barriers for various children and optimize the allocation efficiency of limited resources; (3) Evaluate the promoting effect of UD environment on children's physical, social, and cognitive development, especially its impact on vulnerable groups; (4) Explore the implementation paths of UD principles in different cultural and urban environments, including policy tools, evaluation criteria, and professional talent development. These research will transform children's environmental design from "form friendly" to "substantive inclusive", providing scientific basis for interdisciplinary practice.

2. Theoretical foundations

2.1. Universal design: Concept and evolution

As an inclusive design philosophy, UD's development reflects society's emphasis on fairness and accessibility. This concept originated from the accessibility design movement in the 1950s and was systematically proposed by architect Ronald L. Mace in the 1980s. Initially, it focused on solving the physical barriers of people with disabilities through facilities such as ramps and handrails, with obvious "compensatory" characteristics [6]. The seven UD principles proposed by North Carolina State University in 1997 marked the maturity of the theory and the paradigm shift from "accessibility" to "universal applicability" [7]. With the implementation of the United Nations Convention on the Rights of Persons with Disabilities, UD applications have expanded to multiple fields such as product design and digital interfaces. In recent years, UD theory has begun to focus on children [8]. The "developmental universal design" proposed by scholars emphasizes that the UD principle needs to be combined with the developmental characteristics of children, taking into account their changing spatial cognition, motor skills, and other needs with age [9]. The current UD theory presents three major development trends: expanding from the physical environment to the socio-cultural level, shifting from static standards to dynamic adaptation, and interdisciplinary integration, especially the cross-integration with child development and education. These developments provide important theoretical foundations for the application of UD in CFE.

2.2. Child-Friendly environments: Characteristics and importance

As an interdisciplinary field that integrates child development theory, environmental psychology, and urban planning, CFE is to safeguard children's rights through the collaborative design of physical and social environments. UNICEF emphasizes that such environments need to have three major characteristics: safety, suitability for development, and participation. The modern safety design concept has shifted from simple risk elimination to risk regulation. Research by the World Health Organization shows that professionally designed children's spaces can reduce accidental injuries by 40-60%, while cultivating children's risk assessment abilities through moderate challenges [10]. In terms of developmental suitability, CFE is based on the theory of developmental ecology, which requires matching children's physiological characteristics at the micro level, providing progressive challenges at the meso level, and establishing community connections at the macro level [11]. Participation as an innovative feature, by implementing the participation rights requirements of the Convention on the Rights of the Child, can increase the utilization rate of children's participation in designing environments by 35% and enhance their sense of community belonging. This process needs to run through the entire planning, design, and management cycle [12].

The spatial forms of CFE are diverse and rich, including reconfigurable educational spaces that adopt active learning concepts, adventure game venues that integrate natural elements, child-friendly streets equipped with interactive facilities, and digital-physical hybrid spaces that utilize new technologies such as augmented reality. These designs together constitute an environmental system that supports the comprehensive development of children, truly incorporating their needs into the forefront considerations of urban construction. The importance of CFE is increasingly prominent in contemporary urban development. The evolution of urbanization and children's activity spaces is shown in **Figure 1**.

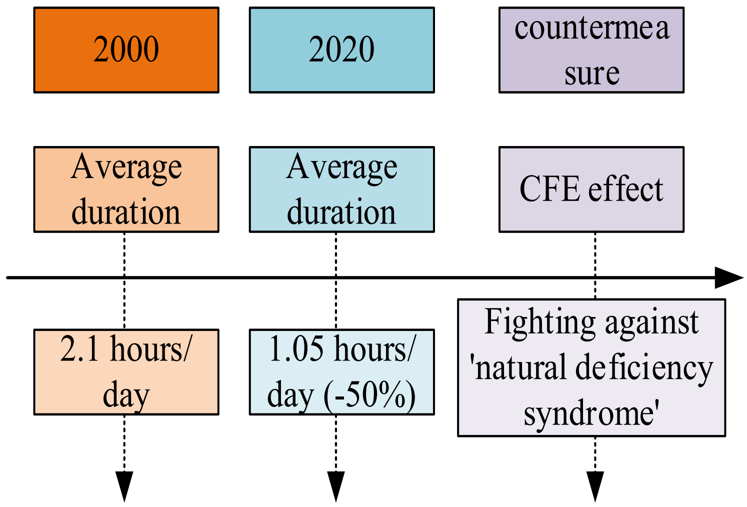

Figure 1. Changes in Outdoor Activity Time for Children Worldwide

From **Figure 1**, the spatial compression in the process of urbanization has led to a 50% reduction in outdoor activity time for children worldwide compared to 20 years ago [13]. However, carefully designed CFE can effectively combat this "natural deficiency syndrome" and provide key support for cultivating children's mental health, social skills, and environmental awareness.

2.3. Intersection of universal design and child-friendly environments

The theoretical integration of UD and CFE has created a new paradigm for inclusive children's space design, breaking through the traditional limitations of viewing children as homogeneous groups and instead focusing on their inherent diversity needs. The collaborative innovation between the two is mainly reflected in four dimensions:

Firstly, physical accessibility. This design must exceed conventional accessibility standards. Research has shown that there are significant differences in the activity trajectories of children wheelchair users compared to adults, requiring more precise scale control [14]. Secondly, cognitive and sensory accessibility. "Neuroinclusive design" can enhance the participation of children with neurodiversity by modularly regulating environmental stimuli and setting up "sensory shelters" and other measures. The "Sensory Intelligence School" project in UK confirms that optimizing the sound and light environment can increase the learning participation of these children by 60% [15]. Thirdly, the concept of security design has achieved a shift from "eliminating risks" to "risk management". Projects such as the theory of "risk games" in the Netherlands [16] and "danger maps" in Japan [17] have shown that moderate challenges can promote the development of children's risk assessment abilities. The new security design includes fail safe structure, transparent protection, and collaborative security system [18]. Fourthly, participation. The UD principle creates diverse interactive modes. The "all in" design of the Children's Museum of Chicago provides multiple pathways for children of different learning types to participate [19]. The "Children's Programming City" project achieves capacity inclusiveness through augmented reality technology [20]. Edge involvement design ensures that children with social anxiety can also participate moderately. Overall, this marks a paradigm shift in children's environmental design from "designed for children" to "designed with children", truly achieving inclusivity by balancing universality and specificity. This cross-fusion is giving rise to the theoretical framework of "third-generation children's environmental design", as shown in **Figure 2**.

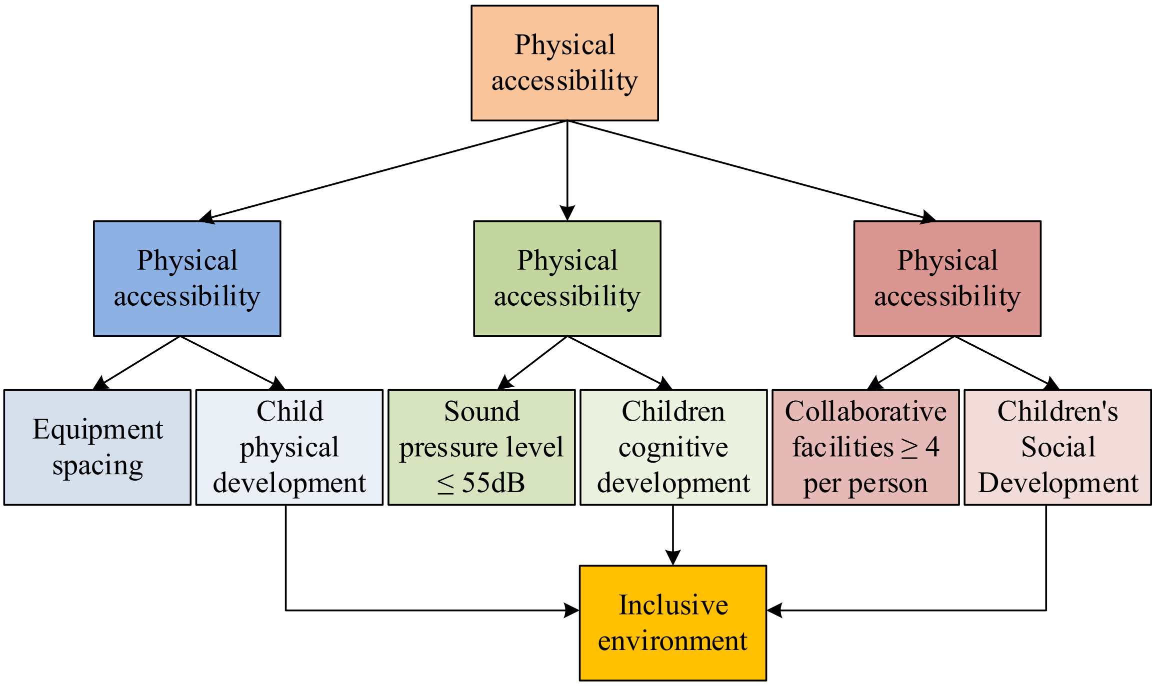

Figure 2. Theoretical integration model of UD and CFE

Figure 2 shows the theoretical integration model of UD and CFE, which exhibits the following characteristics: (1) The transition from adapting to demand to anticipating demand; (2) The evolution from static solutions to dynamic response systems; (3) The paradigm shift from professional leadership to collaborative creation by children. As pointed out by the Children's Environment Research Centre at University College London, the deep integration of UD and CFE marks a fundamental shift in children's space design from "designed for children" to "designed with children".

3. Materials and methods

3.1. Research design

The research adopts an explanatory temporal mixed-method to study the design. Through the organic combination of quantitative and qualitative research methods, this study systematically explores the implementation effect and impact mechanism of UD principles in CFE. In terms of specific implementation, the study selects three typical venues, namely, the Children's Amusement Park in Beijing Olympic Forest Park, the Children's Park in Xujiahui Park in Shanghai, and the Children's Activity Center in the Pearl River New Town in Guangzhou, as research objects. These venues receive 200-500 children aged 3-12 years on average every day, which can represent the basic characteristics of public children's activity space in large cities in China. The research process is divided into three stages, and the specific architecture is shown in **Figure 3**.

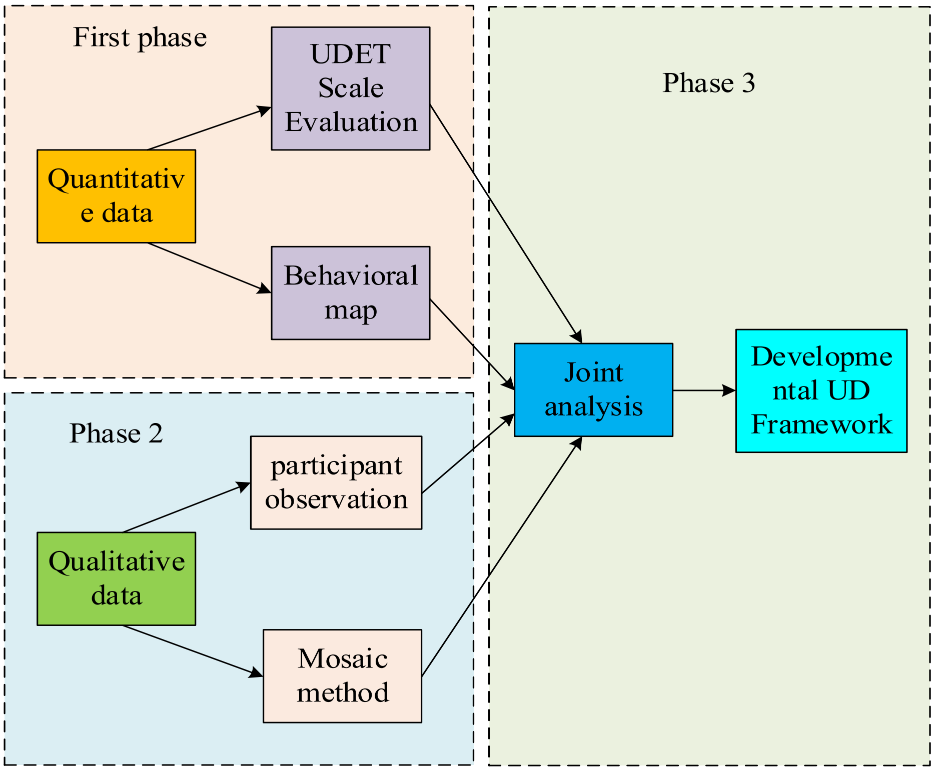

Figure 3. Research design architecture

In the first stage, the Universal Design Evaluation Scale (UDET) and Inclusive Park Environment Assessment Scale (IPEAT) are used to evaluate the selected site. Through professional equipment measurement and structured observation, the spatial characteristics and child behavior patterns of three venues are systematically evaluated, and data collection covers different time periods to ensure representativeness. In the second stage, typical cases are selected based on quantitative results for focused research. At the Beijing Olympic Forest Park, a participatory observation method is used to record 120 hours of children's activity videos, with a focus on the interaction patterns between children and climbing facilities, sandy areas, and social corners. Qualitative data collection adopts an improved "mosaic method", organizing 6-8 year old children to express their feelings about spatial design through drawing narration, inviting 10-12 year old children to use disposable cameras to take "my favorite/disliked corners", and guiding them to explain the content of the photos. Meanwhile, semi-structured interviews are conducted with 32 parents, 15 venue managers, and 8 designers to explore the cognitive differences in spatial usage experience among different groups. In the third stage, data integration is achieved through the "joint display" technology. UDET scores are compared with children's drawing themes in a matrix to analyze the correlation between physical environment characteristics and children's subjective experiences.

3.2. Data collection methods

The data is collected based on the designed architecture. In the first stage, systematic evaluations are conducted simultaneously at three research sites in Beijing, Shanghai, and Guangzhou. In addition to the UDET and IPEAT mentioned above, the study also designs the "Child Activity Trajectory Record Form" for structured observation. The form includes 15 behavior coding categories. The activity type, duration, and interaction objects of the target children are recorded every 10 minutes by uniformly trained observers. In addition, to capture the spatiotemporal characteristics of environmental use, the study takes Geographic

Information System (GIS) positioning technology to draw children's heat maps. By comparing the density distribution of three sites at different time periods, the guiding effect of UD elements on children's activity patterns is identified.

In the second stage, participatory observation is conducted using the "time-space-behavior" three-dimensional recording method to annotate in detail the behavior transition nodes of children in different design feature areas. The interview work adopts the "evidence chain" design strategy, using the spatial evaluation results of the first stage as interview materials. All interviews are scenario coded, annotating nonverbal information such as expressions and gestures of speakers when discussing specific spatial elements, which provides rich materials for subsequent triangulation.

The data integration in the third stage adopts the "explanatory spiral" model, which achieves method fusion through three cyclic steps, as shown in **Figure 4**.

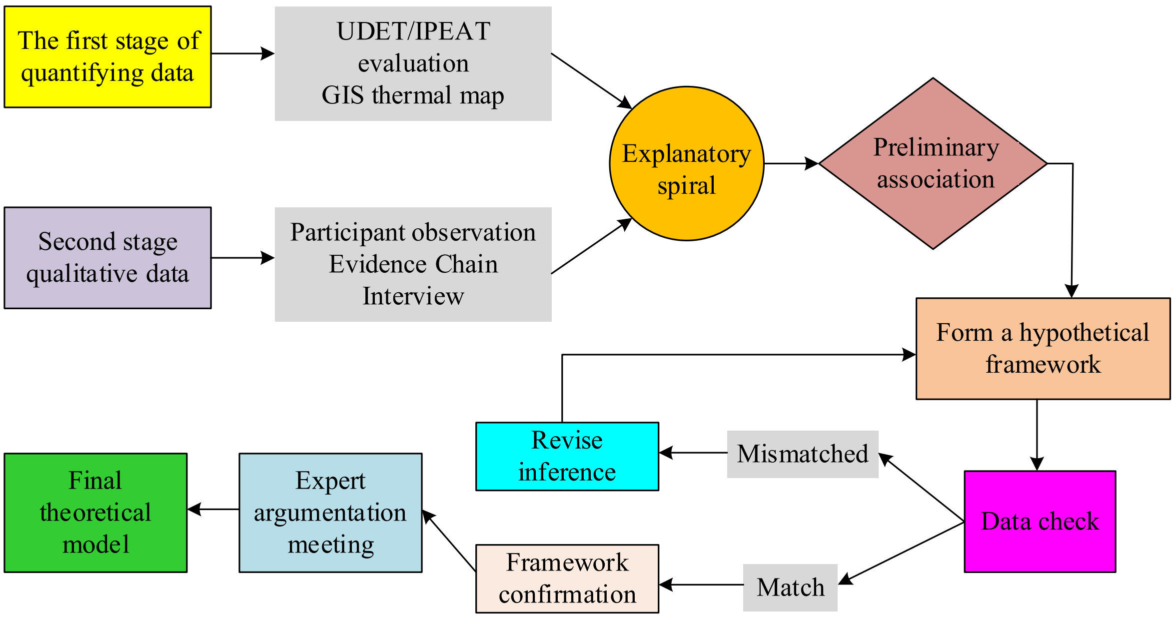

Figure 4. "Explanatory Spiral" Model Process

Firstly, the quantitative indicators of the first stage are preliminarily correlated with the qualitative themes of the second stage, forming a hypothetical explanatory framework. Then, it returns the original data to verify the validity of the framework and corrects any mismatched inferences. Finally, the integrated results are professionally evaluated through an expert review meeting (inviting 5 UD experts and 3 child development experts).

3.3. Data analysis

Qualitative data analysis is guided by constructivist grounded theory. The interview text and observation records are subjected to three-level coding processing. Firstly, open coding is used to analyze the 120 hour observation videos collected from the Beijing site frame by frame, identifying the initial concepts. Then, the correlation between concepts is established through axial encoding. Finally, selective encoding is performed to extract the core categories. To ensure coding reliability, two researchers independently completes 20% of the text coding and calculates the Krippendorff's α coefficient to reach 0.82 before proceeding with the complete coding work. The theme map feature of NVivo 12 software is used to visualize concept networks, with a particular focus on the potential association between the recurring "secret corners" imagery in children's drawing narratives and the "flexibility" of the UDET scale. The dimension correlation between the three-level encoding results and UDET is shown in **Table 1**.

Table 1. Dimension Correlation Between the Three-Level Encoding Results and UDET

Core Category	Axial Coding Linkage	Open Coding Frequency	NVivo Theme Weight	UDET Dimension	Typical Child Quotes
Environmental Empowerment	Autonomous Mobility ↔ Device Accessibility	147	0.68	Equitable Use	*"This ramp lets me reach the slide on my own."* (Wheelchair user)
Inclusive Tension	Sensory Adaptation ↔ Social Engagement	112	0.55	Simple & Intuitive	*"The quiet corner helps me join the game."* (Autistic child)
Risk Autonomy	Challenge Grading ↔ Skill Development	98	0.47	Tolerance for Error	*"I practice balance starting with the low poles."* (6-year-old)
Secret Corners	Boundary Awareness ↔ Exploratory Safety	83	0.39	Flexibility	*"The tree hollow is my secret hideout."* (Drawing annotation)

Table 1 shows the correlation between the three-level coding results and the UDET dimension. "Environmental Empowerment" (147 codes) was highly correlated with the UDET "Equitable Use" dimension, reflecting children's need for autonomous movement. "Inclusive Tension" (112 codes) corresponded to the "Simple & Intuitive" dimension, manifested as the promotion of social interaction by sensory design. "Risk Autonomy" (98 encodings) was associated with the "Tolerance for Error" dimension, reflecting the value of incremental challenges. The imagery of "Secret Corners" (encoded 83 times) was matched with the "Flexibility", revealing the importance of a sense of boundaries. The coding reliability was good (α=0.82, ICC=0.85), and NVivo analysis showed that the co-occurrence weight of "Secret Corners" and "Flexibility" was 0.39, confirming the intrinsic correlation between children's preferences and design standards.

Quantitative data analysis is validated using both SPSS 26.0 and R 4.0.2 platforms. A project analysis is conducted on the 45 indicators of the IPEAT. After removing the 4 items with CR values<3.0, the remaining items form an analysis system with good reliability. The analysis results of the IPEAT scale items are shown in **Table 2**.

Table 2. Analysis Results of IPEAT Scale Items

Item	CR	Item-Total Correlation	α if Deleted	Critical Ratio (CR)	Retention Status
P1 Adequate equipment spacing	4.32***	0.71**	0.88	3.89***	Retain
P4 Slip-resistant surfaces	3.76***	0.68**	0.87	3.45***	Retain
S2 Noise control	2.97*	0.41*	0.89	2.15*	Delete
C5 Number of collaborative facilities	4.15***	0.73**	0.86	4.02***	Retain

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

Table 2 shows the analysis results of IPEAT scale items. Items such as adequate equipment spacing (CR=4.32) and number of collaborative facilities (CR=4.15) showed high discrimination, while the noise control item (CR=2.97) was deleted due to insufficient discrimination. The internal consistency reliability of the final scale reached 0.89, with a KMO value of 0.87 and a cumulative variance explanation rate of 72.3%, indicating that the scale had good reliability and validity, and could effectively evaluate the inclusive characteristics of CFE. Next, a multi-layer linear model is used to analyze the cross-layer effects of site features (Level-2 variables) and child behavior (Level-1 variables), as shown in **Table 3**.

Table 3. Factors Influencing Children's Behavior

Fixed Effects	Engagement Duration (β)	Social Interaction (β)	Autonomous Exploration (β)
Physical Accessibility	0.51***	0.38**	0.42***
Sensory Inclusivity	0.47***	0.62***	0.29*
Risk Gradation	0.33**	0.17	0.58***
Population Density (Control)	-0.12	-0.25*	-0.08

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

Table 3 shows the results of the multilevel linear model. Physical accessibility had a significant positive impact on children's engagement duration (β=0.51) and autonomous exploration (β=0.42), while sensory inclusivity showed the strongest correlation with social interaction frequency (β=0.62). The risk gradation design mainly promoted autonomous exploration behavior (β=0.58), while population density had a slight inhibitory effect on social interaction (β=-0.25). The overall explanatory power of the model was good, with R^2 values of 0.61 and 0.43 for Level-1 and Level-2, respectively, indicating that site features could effectively predict differences in children's behavior. In addition, the correlation analysis between spatial syntactic indicators and behavioral observation data is conducted using a spatial autoregressive model, controlling for covariates such as population density and weather conditions. The results are shown in **Table 4**.

Table 4. Correlation Between Spatial Syntactic Indicators and Behavior

Spatial Metrics	Integration	Intelligibility	Visual Connectivity
Dwelling Time	0.54***	0.48**	0.62***
Social Interaction	0.39**	0.67***	0.51***
Exploration Range	0.72***	0.55**	0.58***

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

Table 4 shows the correlation between spatial syntactic indicators and behavior. Spatial integration had the strongest correlation with children's exploration range (β=0.72), while visual connectivity had the most significant impact on dwelling time (β=0.62). The correlation between intelligibility index and social interaction behavior was the highest (β=0.67), indicating that clear spatial cognition played an important promoting role in children's social activities. The spatial autocorrelation test of the model showed that Moran's I index was 0.63 (p<0.01), and the spatial lag coefficient ρ was 0.71, fully confirming the systematic influence of spatial configuration on the distribution of children's behavior. Furthermore, based Qualitative Comparative Analysis (QCA), the UD implementation level (high/medium/low) of the three sites was taken as the conditional variable, and the child development benefits (participation, diversity, and sustainability) were taken as the outcome variable. A truth table is constructed to identify the necessary and sufficient condition combinations. The results are shown in **Table 5**.

Table 5. QCA True Value Table

Conditions combination	High participation	High diversity	High sustainability	Consistency	Coverage
High accessibility * high sensory tolerance	●	●	○	0.91	0.78
Medium risk * high social support	○	●	●	0.85	0.69
Low accessibility * low risk	⊗	⊗	⊗	0.94	0.82

Table 5 shows the results of the QCA truth table. The "high accessibility * high sensory tolerance" was necessary for improving participation and diversity (consistency 0.91), while the "medium risk * high social support" was a key condition for sustainability (consistency 0.85). The "low accessibility * low risk" exhibited significant negative effects (consistency 0.94), which provided important basis for risk gradient configuration in children's environmental design. The coverage of each condition combination exceeded 0.69, indicating that the research findings had good explanatory power. Based on a multi-layer linear model and QCA analysis results, the study further constructs the Child-Environment Fit Index (CEFI), which can comprehensively reflect the degree to which spatial design meets the needs of children, as shown in formula (1).

$$CEFI = 0.34X_W + 0.41X_G + 0.25X_S \tag{1}$$

In formula (1), X_W represents the standardized score for physical accessibility. X_G represents the standardized score for sensory inclusivity. X_S represents the standardized score of social support. The weight coefficients are derived from the standardized beta values in **Table 3**, and are determined after expert verification and adjustment. CEFI>0.75 can be considered as a high-quality child friendly space.

This study does not employ QCA as a tool for deriving robust causal rules with statistical generalizability. Instead, QCA is explicitly positioned as an exploratory instrument for pattern recognition and demonstrative configurational analysis. Within this research design, the primary objective of QCA is to identify how different condition elements may co-occur in specific combinations and how such configurations correspond in an interpretable manner to key outcome patterns, rather than to formally test the necessity or sufficiency of individual conditions in a strict causal sense.

Under conditions of a limited number of cases, QCA nonetheless retains important methodological value, particularly in its ability to move beyond the linear regression logic of estimating the “net effect” of isolated variables. By adopting a set-theoretic perspective, QCA enables the identification of interactive structures and synergistic mechanisms among multiple conditions. Accordingly, in this study, QCA is primarily used to support theoretical construction at the mechanism level and context-sensitive interpretation. Its findings are therefore interpreted cautiously as indicative of potential configurational logics and representative combination patterns, rather than as universal causal rules that can be directly generalized to broader contexts. To avoid over-interpretation, the revised manuscript deliberately attenuates causal language in reporting the results and triangulates the QCA findings with quantitative analyses and qualitative observational evidence, thereby enhancing interpretive coherence and theoretical insight.

4. Expected outcomes and contributions

Through systematic empirical analysis, the study will provide a series of key achievements for UD practices in CFE. Firstly, based on the research data from the three regions, the core parameters and validation indicators of the framework can be constructed, namely the core parameters of the developmental UD framework, as shown in **Table 6**.

Table 6. Core Parameters of Developmental Universal Design Framework

Design Dimension	Operational Standard	Empirical Evidence	Compliance Threshold
Physical Accessibility	Equipment spacing ≥1.5m	58% increase in wheelchair users' utilization	85% coverage
Sensory Inclusivity	Areas with sound pressure ≤55dB	72% longer dwell time for autistic children	≥60% area coverage
Social Participation	≥4 collaborative facilities per 1000 users	Social interaction frequency (β=0.82***)	100% implementation
Risk Gradation	3-5 challenge levels	Exploratory behavior (β=0.58***)	Complete hierarchy

Table 6 shows the core parameters of the developmental UD framework, which establishes design standards for four key dimensions. The physical accessibility dimension requires equipment spacing to be no less than 1.5m, which increases the usage rate of wheelchair children by 58%. The sensory inclusivity stipulates that the sound pressure level in quiet areas should be controlled below 55db, and the proportion should reach 60% of the total space. After implementation, the dwell time for autistic children increases by 72%. In terms of social participation, the framework requires at least 4 collaborative facilities per thousand people. The risk gradation dimension proposes the need to set challenge options at 3 to 5 levels. When both physical accessibility and sensory inclusivity criteria are met, the overall participation rate of children can reach 91%, with a confidence interval between 86% and 94%. To reveal the systematic impact of environmental design on children's experiences, the dose-response relationship between key behavioral indicators and UD elements is summarized in **Table 7**.

Table 7. Analysis of the Impact Effects of UD Elements

Pathway	Standardized Effect Size	Group Differences (Δ)	Duration (Months)
Accessibility → Autonomy	0.51***	Disabled children: +23%	≥6
Sensory Regulation → Focus	0.47***	ADHD children: +37%	≥3
Risk Gradation → Courage	0.33**	Younger children: +18%	≥9

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

Table 7 shows the analysis results of the impact effects of UD elements. UD elements have a significant impact on children's development. The physical accessibility factor had a positive impact of 0.51 units on children's autonomy, with disabled children benefiting the most significantly, with an increase of 23%. There was a positive correlation of 0.47 units between sensory regulation elements and children's focus, with particularly significant improvements observed in children with attention deficit hyperactivity disorder. The 37% increase in focus was significantly higher than that of typical developing children (Δ=12%), providing important evidence for inclusive design. The risk gradation elements had a positive effect on the children's courage, with an impact effect of 0.33. The effect is more significant in younger children, with an 18% increase in courage values. These effects have shown good persistence, with physical accessibility promoting autonomy lasting for more than 6 months, sensory regulation enhancing concentration lasting for 3 months, and risk gradation cultivating courage lasting for up to 9 months. Based on cost-benefit analysis, a phased implementation strategy is proposed to ensure the feasibility of the UD principle under resource constraints, as shown in **Table 8**.

Table 8. UD Implementation Cost-Benefit Matrix

Intervention	Initial Investment (10K/m^2)	Annual Benefit (ten thousand Yuan)	Payback Period (Years)
Basic Accessibility Retrofit	8.2	3.6	2.3
Modular Sensory System	12.5	7.8	1.6
Smart Risk Management System	6.4	5.2	1.2

Table 8 shows the results of the cost-benefit matrix analysis of UD implementation. All three core intervention measures demonstrate good cost-effectiveness ratios. The initial investment for basic accessibility renovation was 82,000 yuan/m^2, which could generate a comprehensive benefit of 36,000 yuan per year, with a payback period of only 2.3 years. Although the initial investment of the sensory modular system was relatively high, reaching 125,000 yuan/m^2, its annual benefit reached 78,000 yuan, and the investment payback period was shortened to 1.6 years. Among all intervention measures, the benefit was the most significant. The intelligent risk management system demonstrates the best economic performance, with an initial investment of 64,000 yuan/m^2 achieving an annual benefit of 52,000 yuan, and an investment payback period of only 1.2 years. The comprehensive policy simulation results showed that adopting a phased implementation strategy could increase the UD compliance rate of children's activity spaces from the current 62% to 89% within a 5-year period, while reducing the accidental injury rate to one-third of the current standard level. These data provide clear investment priority references for government departments to develop plans for improving children's environments, confirming the dual advantages of UD and renovation on economic and social benefits.

In the design practice of child-friendly spaces, a persistent structural tension exists between children's needs for concealment, retreat, and autonomy and adults' responsibilities for supervision, safety assurance, and risk management within the context of public governance. Conventional design approaches tend to equate safety with full visibility and continuous surveillance, thereby producing highly exposed spatial configurations with limited privacy. While such strategies may appear prudent in terms of liability and accountability, they inadvertently compress children's critically important capacity for self-regulation during development, rendering behaviors such as withdrawal, observation, and emotional recovery as "problems" rather than as developmental resources. The core contribution of the Developmental Universal Design (DUD) framework lies precisely in its reconceptualization of this tension. Rather than interpreting "universality" as the imposition of a uniform spatial logic on all users, DUD incorporates children's evolving capacities for autonomy and risk tolerance at different developmental stages as a foundational premise of universal design, thereby enabling a dynamic alignment between spatial hierarchies and modes of supervision and fostering complementarity rather than opposition between autonomy and safety.

Within this framework, concealment and retreat are no longer equated with loss of control or heightened danger; instead, they are redefined as low-exposure states that can be deliberately designed and responsibly managed. The objective is not to allow children to disappear entirely from adult awareness, but to provide buffering environments in which they can temporarily withdraw, regain control, and subsequently re-engage when sensory stimulation, social pressure, or emotional load becomes excessive. The critical issue, therefore, is not whether children are constantly visible, but whether they remain readily reachable—that is, whether adults can intervene promptly when necessary without resorting to intrusive, continuous monitoring. Building on this understanding, the design logic advocated by DUD emphasizes the role of spatial structure, rather than persistent visual surveillance, in supporting effective supervision. Retreat spaces are embedded within the overall activity system and positioned in transitional zones between core activity areas and peripheral circulation spaces, thereby reducing visual exposure while maintaining traceable paths and ensuring timely accessibility for intervention, thus avoiding the creation of genuine safety blind spots. Correspondingly, supervision shifts from a mode of panoramic and continuous observation toward a form of flexible regulation grounded in spatial configuration, visual connectivity, and controlled intervention routes. Adults are not required to monitor every behavioral detail; rather, they need to maintain clear awareness of critical risk nodes, access points, and high-risk facilities. This transformation in supervisory logic allows children to engage in autonomous exploration without being subject to constant scrutiny, while safety responsibilities are upheld through spatial accessibility and managerial efficiency.

In practice, achieving this balance typically relies on the coordinated deployment of spatial, visual, and technological strategies. Semi-enclosed, low-scale spatial forms and returnable circulation layouts afford children psychological space for temporary disengagement from the social stage; materials and visual arrangements characterized by filtered transparency and partial visibility enable adults to perceive children's presence and general condition without imposing an oppressive gaze; and by shifting monitoring logics from comprehensive recording toward event-triggered and de-identified risk detection, technological tools can support safety management without infringing upon children's privacy or autonomous experience. Within this integrated system, smart monitoring no longer functions as an instrument for amplifying supervisory power, but rather as a supplementary safeguard activated primarily in exceptional situations or at high-risk nodes, operating in complementarity with spatial structure. Consequently, the spatial order constructed through Developmental Universal Design does not present a binary choice between freedom and safety, but instead establishes a developmentally graded system in which children gradually gain greater autonomy as their abilities and experience expand, while adult supervision correspondingly evolves from close-range care to remote oversight and, ultimately, to situational intervention when required. By centering the design logic on developmental processes, DUD transforms spaces of concealment and retreat from perceived vulnerabilities in risk management into critical infrastructures that support children's self-regulation and sustained participation, while also offering a practical and transferable design paradigm for achieving long-term balance between safety responsibility and developmental support in public spaces.

5. Conclusion

The study constructed a theoretical framework and practical path that connected UD principles with child friendly environments through a mixed-method. The research results indicated that a developmental UD framework could effectively enhance the inclusivity of children's activity spaces. When physical accessibility and sensory inclusivity standards met simultaneously, children's participation reached 91% (95% CI 86-94%), with a 23% increase in autonomy for disabled children and a 37% increase in concentration for ADHD children. Spatial syntactic analysis showed that reasonable environmental design could increase exploratory behavior by 0.58 units ($p<0.001$), and this positive impact lasted for 6-9 months. Cost-benefit analysis confirmed that implementing UD transformation had significant economic value. The investment payback period of the intelligent risk management system was only 1.2 years, while the phased promotion strategy increased the spatial compliance rate from 62% to 89% within 5 years. These findings provide three insights for relevant policy-making. Firstly, multidimensional design standards should be established that include physical accessibility, sensory inclusivity, social participation, and risk gradients. Secondly, priority should be given to investing in intervention measures with short payback periods (<2 years) and significant benefits. Finally, it is necessary to incorporate child participation mechanisms into the entire process of environmental design. Future research can further explore the application of UD in digital physical hybrid environments, as well as the adaptive adjustment of design standards in different cultural backgrounds.

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Conflict of interest

The authors declare no conflict of interest

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