The Impact of Design Environment Quality on Early Childhood Design Thinking Development: A Longitudinal Neuroimaging Study

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Abstract

Background: Early childhood represents a critical period for cognitive development, particularly in creative and design thinking abilities. While previous research has established the importance of environmental factors in general cognitive development, the specific impact of design-rich environments on design thinking capabilities remains understudied. This longitudinal study investigates how the quality of the design environment influences the development of design thinking skills in early childhood through comprehensive behavioral and neuroimaging assessments. **Methods:** We conducted a 48-month longitudinal study with 224 children aged $\mathbf{6-48}$ months, categorized into high (n=111) and low (n=113) design environment quality groups based on the Design Environment Quality Index (DEQI). Participants underwent comprehensive assessments including the Children's Design Thinking Assessment Scale (CDTAS), Innovation Cognitive Ability Test (ICAT), and Visual-Spatial Creativity Index (VSCI). Neuroimaging data was collected using structural and functional magnetic resonance imaging to examine brain development patterns. In addition, a randomized controlled intervention study was conducted with 113 children from low-design environment backgrounds. **Results:** Children in high design environment quality groups demonstrated significantly superior performance across all cognitive measures (CDTAS: $\mathbf{72.6 \pm 13.6}$vs $\mathbf{51.9 \pm 12.2}$, $\boldsymbol{p < 0.001}$, Cohen's $\boldsymbol{d = 1.604}$; ICAT: $\mathbf{56.3 \pm 10.8}$ vs $\mathbf{40.4 \pm 10.6}$, $\boldsymbol{p < 0.001}$,

$\boldsymbol{d} = \mathbf{1.489}$; VSCI: $\mathbf{64.8 \pm 12.7}$ vs $\mathbf{47.2 \pm 11.8}$, $\boldsymbol{p} < \mathbf{0.001}$, $\boldsymbol{d} = \mathbf{1.428}$). Neuroimaging analyses revealed enhanced functional connectivity in creative networks ($\boldsymbol{p} < \mathbf{0.001}$) and increased prefrontal and parietal cortex in the high design environment group. Longitudinal growth trajectories showed accelerated development of design thinking abilities for children in enriched design environments. The early design education intervention demonstrated significant improvements in design thinking scores (effect size $\boldsymbol{d} = \mathbf{0.676}$, $\boldsymbol{p} < \mathbf{0.001}$). **Conclusions:** Design environment quality exerts profound and lasting effects on early childhood design thinking development, with impacts observable at both the behavioral and neural levels. These findings highlight the critical importance of design-rich environments in fostering creative cognitive abilities during sensitive developmental periods. The results support the implementation of early design education interventions and provide evidence-based guidelines to optimize developmental environments.

Keywords: Design thinking, Early childhood development, Neuroimaging, Eenvironmental enrichment, Cognitive development, Design education

1 Introduction

The early years of human development represent a period of unprecedented neural plasticity and cognitive growth, during which environmental influences can profoundly shape lifelong learning trajectories and cognitive capabilities [1]. Although extensive research has documented the impact of socioeconomic factors and general environmental enrichment on cognitive development [2, 3], the specific influence of design-rich environments on the emergence and development of design thinking abilities remains largely unexplored. This gap in knowledge is particularly significant given the increasing recognition of design thinking as a fundamental 21st-century skill essential for innovation, problem-solving, and creative expression [4, 5].

Design thinking, conceptualized as a human-centered approach to innovation that integrates the needs of people, the possibilities of technology, and requirements for business success, encompasses multiple cognitive domains including empathy, problem definition, ideation, prototyping, and testing [6]. These capabilities emerge early in development, with foundational skills observable in infancy and toddlerhood through behaviors such as exploratory play, creative problem-solving, and innovative use of materials [7, 8]. However, the environmental conditions that optimize the development of these abilities during critical periods remain poorly understood. The theoretical foundation for investigating design environment effects on cognitive development draws from multiple converging lines of research. Environmental enrichment studies in both animal models and human populations have consistently demonstrated that stimulating, resource-rich environments promote enhanced neural development, increased synaptic density, and improved cognitive performance[9, 10]. Specifically, environments characterized by novelty, complexity, and opportunities for active exploration have been shown to accelerate brain development and enhance learning capacity [11]. These findings align with ecological systems theory, which emphasizes the profound influence of environmental contexts on developmental outcomes[12]. In the domain of creativity and design cognition, research has identified several environmental factors that support creative development, including access to diverse materials, opportunities for open-ended exploration, exposure to aesthetic experiences, and supportive social interactions [13, 14]. However, most existing studies have focused on school-age children or adults, leaving a significant gap in understanding how design environments influence the earliest stages of creative cognitive development. This limitation is particularly problematic given evidence that creative abilities show rapid development during the first years of life and may be especially sensitive to environmental influences during this period[15, 16]. Recent advances in developmental neuroimaging have provided unprecedented opportunities to examine the neural mechanisms underlying early cognitive development and environmental influences on brain structure and function [17, 18]. Studies using functional magnetic resonance imaging (fMRI) have identified specific brain networks associated with creative thinking, including the default mode network, executive control network, and salience network [19, 20] . These networks show dynamic developmental patterns during early childhood, with environmental factors potentially influencing their maturation and connectivity patterns [21] . The present study addresses these knowledge gaps by conducting the first comprehensive longitudinal investigation of design environment effects on early childhood design thinking development. We developed a novel theoretical framework that conceptualizes design environment quality as a multidimensional construct encompassing design resource availability, creative tool accessibility, and design culture exposure. This framework builds upon established models of environmental enrichment while incorporating specific elements relevant to design and creative development.

Our research addresses three primary objectives. First, we examine the relationship between design environment quality and the development of design thinking abilities across multiple cognitive domains during the critical period from 6 to 48 months of age. Second, we investigate the neural mechanisms underlying these relationships through comprehensive structural and functional neuroimaging assessments. Third, we evaluate the effectiveness of early design education interventions in promoting design thinking development among children from low design environment backgrounds. The significance of this research extends beyond theoretical contributions to developmental science. Understanding how design environments influence early cognitive development has important implications for educational policy, early intervention programs, and family support services. As societies increasingly recognize the importance of creativity and innovation for economic and social progress, identifying the environmental conditions that foster these abilities from the earliest stages of development becomes a critical priority [22, 23]. Furthermore, this research contributes to growing efforts to address developmental inequalities by identifying modifiable environmental factors that can be targeted through intervention programs. If design environment quality significantly influences cognitive development, then providing access to design-rich environments for all children, regardless of socioeconomic background, could serve as an important strategy for promoting equity in developmental outcomes [24, 25]. The current study employs a rigorous longitudinal design with comprehensive behavioral and neuroimaging assessments to provide definitive evidence regarding the impact of design environments on early childhood development. By combining multiple methodological approaches and examining both behavioral outcomes and underlying neural mechanisms, this research provides a comprehensive understanding of how environmental factors shape the emergence of design thinking abilities during critical developmental periods.

2 Literature Review

2.1 Theoretical Foundations of Environmental Influence on Cognitive Development

The theoretical understanding of environmental influences on cognitive development has evolved significantly over the past several decades, with converging evidence from multiple disciplines supporting the profound impact of environmental factors on brain development and cognitive abilities [26]. The foundational work of Bronfenbrenner's ecological systems theory established that human development occurs within nested environmental systems, from immediate microsystems to broader macrosystems, each contributing to developmental outcomes [27] . This framework has been particularly influential in understanding how environmental factors operate at multiple levels to influence cognitive development. Environmental enrichment research, initially conducted in animal models, has provided compelling evidence for the plasticity of the developing brain in response to environmental stimulation[28]. Studies with rodents have consistently demonstrated that animals raised in enriched environments, characterized by increased space, novel objects, and social interaction opportunities, show enhanced brain development including increased cortical thickness, dendritic branching, and synaptic density[29, 30]. These neurobiological changes are associated with improved performance on learning and memory tasks, suggesting that environmental enrichment promotes cognitive development through direct effects on brain structure and function.

Translation of these findings to human populations has revealed similar patterns, with children from enriched environments showing enhanced cognitive development and academic achievement [31]. The landmark Perry Preschool Project and other early intervention studies have demonstrated that high-quality early childhood programs can produce lasting improvements in cognitive abilities, educational attainment, and life outcomes [32, 33]. These findings have been supported by neuroimaging studies showing that children from higher socioeconomic backgrounds, who typically have access to more enriched environments, exhibit differences in brain structure and function compared to children from disadvantaged backgrounds [34, 35]. The concept of sensitive periods in development provides additional theoretical support for the importance of early environmental influences[36] . During sensitive periods, the brain exhibits heightened plasticity and responsiveness to environmental input, making these periods particularly important for optimal development [37]. Research has identified multiple sensitive periods for different cognitive abilities, with many occurring during the first years of life when environmental influences may have the most profound and lasting effects[38] .

2.2 Design Thinking and Creative Cognition in Early Development

Design thinking represents a complex cognitive process that integrates multiple domains including creative thinking, problem-solving, empathy, and systems thinking[39] . The development of these capabilities begins early in life, with foundational skills observable in infancy and toddlerhood[40]. Research on early creative development has identified several key milestones, including the emergence of symbolic play around 12-18 months, the development of divergent thinking abilities during the preschool years, and the increasing sophistication of creative problem-solving strategies throughout early childhood [41, 42]. The cognitive neuroscience of creativity has identified specific brain networks associated with creative thinking, including the default mode network (DMN), executive control network (ECN), and salience network[43, 44] . The default mode network, which includes regions such as the medial prefrontal cortex, posterior cingulate cortex, and angular gyrus, is associated with spontaneous thought generation and idea elaboration[45] . The executive control network, encompassing the dorsolateral prefrontal cortex and posterior parietal cortex, is involved in the evaluation and refinement of creative ideas[46] . The salience network, including the anterior insula and dorsal anterior cingulate cortex, facilitates switching between different cognitive modes and networks [47]. Developmental studies have shown that these networks undergo significant maturation during early childhood, with implications for the development of creative abilities [48]. The default mode network shows protracted development, with adult-like connectivity patterns not emerging until adolescence[49] . This extended developmental trajectory suggests that early environmental influences may have particularly important effects on the maturation of creative cognitive networks. Research on environmental factors that support creative development has identified several key elements, including access to diverse materials and tools, opportunities for open-ended exploration and play, exposure to aesthetic experiences, and supportive social interactions that encourage creative expression[50, 51] . However, most existing research has focused on school-age children or adults, with limited investigation of how these factors influence the earliest stages of creative development.

2.3 Environmental Factors in Early Cognitive Development

The home environment has been identified as one of the most important influences on early cognitive development, with multiple dimensions of the home environment contributing to developmental outcomes[52] . The Home Observation for Measurement of the Environment (HOME) inventory has been widely used to assess environmental quality, measuring factors such as learning materials, language stimulation, academic stimulation, and variety in daily stimulation[53] . Studies using the HOME inventory have consistently found positive associations between environmental quality and cognitive development, with effects observable from infancy through school age[54, 55]. Specific environmental factors that have been linked to enhanced cognitive development include the availability of age-appropriate toys and learning materials, opportunities for varied experiences and stimulation, responsive and stimulating interactions with caregivers, and organized physical environments that support exploration and learning[56, 57] . Research has also highlighted the importance of environmental complexity and novelty in promoting cognitive development, with children benefiting from exposure to varied and challenging experiences[58]. The quality of caregiver-child interactions represents another critical environmental factor, with responsive, sensitive, and stimulating interactions promoting optimal cognitive development[59, 60] . Research has shown that caregivers who engage in rich verbal interactions, provide appropriate scaffolding for learning, and encourage exploration and curiosity have children who show enhanced cognitive development[61, 62] . Socioeconomic factors significantly influence environmental quality, with families from higher socioeconomic backgrounds typically having access to more resources, materials, and opportunities that support cognitive development[63]. However, research has also identified specific environmental factors that can be modified to support development regardless of socioeconomic status, suggesting that targeted interventions can help address developmental inequalities[64, 65] .

2.4 Neuroimaging Studies of Early Brain Development

Advances in neuroimaging technology have revolutionized our understanding of early brain development, providing unprecedented insights into the structural and functional changes that occur during the first years of life [66]. Structural MRI studies have documented rapid brain growth during early childhood, with total brain volume increasing dramatically during the first two years of life [66]. This growth is characterized by increases in both gray matter and white matter, with different brain regions showing distinct developmental trajectories[67]. Functional MRI studies have revealed the emergence and maturation of large-scale brain networks during early development[68]. The default mode network, executive control network, and salience network all show developmental changes during early childhood, with implications for cognitive development . Research has shown that the strength and organization of these networks are associated with cognitive abilities, suggesting that environmental factors that influence network development may have important effects on cognitive outcomes[69]. Diffusion tensor imaging (DTI) studies have provided insights into white matter development, showing rapid increases in white matter integrity during early childhood[70] . These changes reflect the myelination of axonal connections, which is critical for efficient neural communication and cognitive development[71]. Environmental factors have been shown to influence white matter development, with children from enriched environments showing enhanced white matter integrity[72].

Studies examining environmental influences on brain development have found significant associations between environmental quality and brain structure and function[73]. Children from higher socioeconomic backgrounds show differences in brain structure, including increased cortical thickness and surface area in regions associated with language and executive function[74]. Functional connectivity studies have also revealed differences in network organization associated with environmental factors[75].

2.5 Early Intervention and Environmental Modification

Research on early intervention programs has provided compelling evidence that environmental modifications can promote cognitive development and reduce developmental inequalities[76]. High-quality early childhood programs that provide enriched environments, responsive caregiving, and educational support have been shown to produce lasting improvements in cognitive abilities and life outcomes[77, 78]. The Abecedarian Project, one of the most comprehensive early intervention studies, provided intensive educational and social services to children from disadvantaged backgrounds from infancy through school age . Long-term follow-up studies have shown that participants in the intervention group had higher IQ scores, better academic achievement, and improved life outcomes compared to control group participants[78] . Neuroimaging studies of Abecedarian participants have revealed differences in brain structure and function that persist into adulthood[79]. Other successful early intervention programs, including the Perry Preschool Project and the Chicago Child- Parent Centers, have demonstrated similar positive effects. These programs typically include multiple components such as high-quality educational programming, family support services, and comprehensive health and social services[80] . Research on specific intervention components has identified several key elements that contribute to program effectiveness, including high-quality caregiver-child interactions, developmentally appropriate curricula, family engagement, and comprehensive support services[81, 82]. Programs that begin early in development and continue for extended periods tend to show the largest and most lasting effects[83].

2.6 Gaps in Current Knowledge and Study Rationale

Despite the extensive research on environmental influences on cognitive development, several important gaps remain in our understanding of how design environments specifically influence the development of design thinking abilities. First, most existing research has focused on general cognitive abilities rather than specific creative and design thinking skills. While creativity research has identified environmental factors that support creative development, these studies have typically examined older children or adults, leaving the earliest stages of creative development understudied.

Second, there is limited research on the specific environmental factors that support design thinking development. While general environmental enrichment has been shown to promote cognitive development, the particular elements of the environment that are most important for design thinking abilities remain unclear. This gap is particularly significant given the multidimensional nature of design thinking, which encompasses empathy, problem definition, ideation, prototyping, and testing.

Third, most studies of environmental influences on cognitive development have relied on behavioral measures, with limited investigation of the underlying neural mechanisms. While neuroimaging studies have begun to examine environmental influences on brain development, few studies have specifically examined how environmental factors influence the development of brain networks associated with creativity and design thinking. Fourth, there is limited research on early intervention programs specifically designed to promote design thinking abilities. While general early childhood programs have shown positive effects on cognitive development, programs specifically targeting creative and design thinking skills are rare, particularly for very young children.

The present study addresses these gaps by conducting the first comprehensive longitudinal investigation of design environment effects on early childhood design thinking development. By examining both behavioral outcomes and underlying neural mechanisms, this research provides a comprehensive understanding of how environmental factors shape the emergence of design thinking abilities during critical developmental periods. The inclusion of an intervention component allows for the evaluation of whether environmental modifications can effectively promote design thinking development in children from disadvantaged backgrounds.

3 Methods

3.1 Study Design and Overview

This study employed a longitudinal cohort design with nested intervention components to examine the impact of design environment quality on early childhood design thinking development. The research was conducted over a 48-month period from January 2019 to December 2023, with comprehensive assessments conducted at seven time points: baseline (T0), 6 months (T1), 12 months (T2), 18 months (T3), 24 months (T4), 36 months (T5), and 48 months (T6). The study protocol was approved by the Institutional Review Board (IRB-2019-001) and conducted in accordance with the Declaration of Helsinki. All parents provided written informed consent, and age-appropriate assent procedures were implemented for older children. The study design incorporated three complementary research components. The primary longitudinal cohort study examined developmental trajectories in children from high and low design environment quality backgrounds. A nested randomized controlled intervention study evaluated the effectiveness of early design education programming for children from low design environment backgrounds. Comprehensive neuroimaging assessments were conducted at baseline and key follow-up time points to examine the neural mechanisms underlying environmental effects on cognitive development.

3.2 Participants

3.2.1 Recruitment and Eligibility

Participants were recruited through multiple channels including pediatric clinics, early childhood centers, community organizations, and social media platforms. Recruitment materials were distributed in multiple languages to ensure diverse participation. Eligibility criteria included: (1) age between 6 and 48 months at enrollment, (2) full-term birth (gestational age $\geq$ 37 weeks), (3) Apgar score $\geq$ 8 at birth, (4) absence of known developmental disorders or neurological conditions, (5) absence of significant hearing or vision impairments, and (6) parental consent for longitudinal participation including neuroimaging assessments.

Exclusion criteria included: (1) preterm birth (gestational age ¡37 weeks), (2) presence of serious congenital conditions, (3) known genetic disorders affecting development, (4) significant sensory impairments, (5) current participation in other research studies involving cognitive interventions, and (6) contraindications to MRI scanning including implanted medical devices or severe claustrophobia.

3.2.2 Sample Size Calculation

Sample size calculations were based on effect sizes reported in previous studies of environmental influences on cognitive development. Assuming a medium to large effect size (Cohen's d = 0.6), alpha level of 0.05, and power of 0.80, the minimum required sample size was calculated as 45 participants per group. To account for anticipated attrition of approximately 20% over the 48-month study period, we aimed to recruit 56 participants per group, for a total target sample of 224 participants.

3.2.3 Final Sample Characteristics

A total of 280 families were initially screened for eligibility, with 56 excluded due to failure to meet inclusion criteria (n=32) or declining participation (n=24). The final enrolled sample consisted of 224 children (111 in the high design environment quality group, 113 in the low design environment quality group). Participant characteristics are presented in Table 1. The sample was well-balanced across groups with respect to key demographic variables. Mean age at enrollment was 24.0 months (SD=10.7), with 49% female participants. Family income ranged from 15, 000 to 150,000 annually, with a median of $48,500. Parental education levels were distributed across high school (30%), bachelor's degree (40%), master's degree (25%), and doctoral degree (5%). Racial and ethnic composition reflected the local community demographics, with 45% White, 25% Hispanic/Latino, 15% African American, 10% Asian, and 5% other or mixed race participants.

3.3 Design Environment Quality Assessment

3.3.1 Theoretical Framework

Design Environment Quality (DEQ) was conceptualized as a multidimensional construct encompassing three primary domains: Design Resource Index (DRI), Creative Tool Accessibility Score (CTAS), and Design Culture Exposure Scale (DCES). This framework was developed based on extensive literature review and expert consultation with specialists in early childhood development, design education, and environmental psychology. The theoretical model posits that optimal design environments provide: (1) abundant and diverse design-related resources and materials, (2) accessible tools and technologies that support creative expression and making, and (3) regular exposure to design culture through activities, experiences, and social interactions. These three domains were hypothesized to work synergistically to create environments that support the development of design thinking abilities.

3.3.2 Design Resource Index (DRI)

The Design Resource Index assessed the availability and quality of design-related resources in the child's primary environment. The assessment included four subscales: Creative Materials Accessibility (0-20 points), Design Tool Diversity (0-20 points), Artistic Work Display (0-15 points), and Creative Space Setup (0-15 points). Total DRI scores ranged from 0-70 points.

Creative Materials Accessibility evaluated the availability of age-appropriate materials for creative expression including drawing and painting supplies, building and construction materials, craft supplies, and natural materials for exploration. Design Tool Diversity assessed access to tools that support making and creating, including basic hand tools, digital devices for creative expression, musical instruments, and specialized equipment for different types of making activities. Artistic Work Display measured the presence and quality of visual displays of creative work in the child's environment, including child-created artwork, professional artistic works, and design objects. Creative Space Setup evaluated the physical organization of spaces to support creative activities, including dedicated areas for making, appropriate storage for materials, and flexible spaces that can be adapted for different types of creative work.

3.3.3 Creative Tool Accessibility Score (CTAS)

The Creative Tool Accessibility Score assessed the child's opportunities to access and use tools that support creative expression and design thinking. The assessment included four subscales: Drawing Tools (0-15 points), Construction Materials (0-15 points), Digital Creative Tools (0-10 points), and Handcraft Materials (0- 10 points). Total CTAS scores ranged from 0-50 points. Drawing Tools evaluated access to various drawing and mark-making implements including crayons, markers, pencils, paints, and digital drawing tools. Construction Materials assessed availability of building and construction toys, blocks, LEGO, and other materials that support three-dimensional creation. Digital Creative Tools measured access to age-appropriate technology for creative expression including tablets with drawing apps, simple programming tools, and digital cameras.

Handcraft Materials evaluated availability of materials for hands-on making activities including clay, playdough, fabric, yarn, and other materials that support tactile creative expression. Each subscale was scored based on both the quantity and quality of available tools, with higher scores indicating greater accessibility and diversity of creative tools.

3.3.4 Design Culture Exposure Scale (DCES)

The Design Culture Exposure Scale assessed the frequency and quality of the child's exposure to design culture and creative activities. The assessment included four subscales: Museum/Exhibition Visits (0-20 points), Design Activity Participation (0-20 points), Family Design Discussions (0-15 points), and Design Media Exposure (0-15 points). Total DCES scores ranged from 0-70 points. Museum/Exhibition Visits evaluated the frequency of visits to museums, galleries, design exhibitions, and other cultural institutions that expose children to design and creative work. Design Activity Participation assessed involvement in structured and unstructured design-related activities including art classes, maker workshops, design challenges, and creative play sessions. Family Design Discussions measured the frequency and quality of conversations about design, creativity, and aesthetic experiences within the family context. Design Media Exposure evaluated exposure to design- related content through books, videos, websites, and other media that introduce children to design concepts and creative processes.

3.3.5 Design Environment Quality Index (DEQI) Calculation

The overall Design Environment Quality Index was calculated using a weighted combination of the three component scores:

$$\text{DEQI} = w_1\,\text{DRI} + w_2\,\text{CTAS} + w_3\,\text{DCES} \tag{1}$$

Weights were determined through principal component analysis of the three component scores, with the first principal component explaining 68% of the variance. The resulting weights were $w_1 = 0.42$, $w_2 = 0.31$, and $w_3 = 0.27$. Total DEQI scores ranged from 0190 points, with participants scoring $\geq$ 75points classified as high design environment quality and those scoring$<$ 75 points classified as low design environment quality.

3.4 3.4 Cognitive Assessment Measures

3.4.1 Children's Design Thinking Assessment Scale (CDTAS)

The Children's Design Thinking Assessment Scale was developed specifically for this study to measure design thinking abilities in early childhood. The assessment was designed to be developmentally appropriate across the age range of 6-48 months, with age-specific versions and scoring criteria. The CDTAS evaluates five core dimensions of design thinking: Empathy (0-25 points), Problem Definition (0-25 points), Ideation (0-25 points), Prototyping (0-25 points), and Testing (0-25 points). Total scores range from 0-125 points. The Empathy subscale assesses the child's ability to observe and understand the needs and feelings of others through structured observation tasks and caregiver reports. For younger children (6-24 months), this includes measures of social attention, emotional responsiveness, and helping behaviors. For older children (25-48 months), more sophisticated empathy tasks are included such as perspective-taking activities and collaborative problem-solving scenarios.

The Problem Definition subscale evaluates the child's ability to identify and articulate problems or needs in their environment. Assessment methods include structured play scenarios where children encounter problems that need to be solved, observation of spontaneous problem identification during free play, and caregiver reports of problem-solving behaviors in daily life.

The Ideation subscale measures the child's ability to generate creative solutions and ideas. Assessment includes divergent thinking tasks adapted for young children, creative play scenarios that encourage idea generation, and measures of flexibility and originality in problem-solving approaches. Tasks are designed to be engaging and age-appropriate while capturing individual differences in creative thinking abilities.

The Prototyping subscale assesses the child's ability to create physical representations of their ideas using available materials. This includes structured making tasks with various materials, observation of construction and building behaviors during play, and evaluation of the child's ability to translate ideas into tangible forms. Scoring considers both the sophistication of the prototypes and the process used to create them.

The Testing subscale evaluates the child's ability to evaluate and refine their ideas and creations. This includes observation of how children interact with their own creations, their responsiveness to feedback from others, and their willingness to modify and improve their work. For older children, more formal testing and iteration activities are included.

3.4.2 Innovation Cognitive Ability Test (ICAT)

The Innovation Cognitive Ability Test was adapted from established measures of creative cognition for use with young children. The ICAT includes three primary components: Divergent Thinking Tests, Convergent Thinking Tests, and Visual-Spatial Reasoning Tests. Total scores range from 0-100 points. Divergent Thinking Tests include age-appropriate versions of classic creativity tasks such as the Alternative Uses Task, where children are asked to think of different ways to use common objects. For younger children, this is implemented through play-based activities where children are given objects and encouraged to explore different uses. The Figural Completion Task asks children to complete partial drawings in creative ways, adapted for different developmental levels.

Convergent Thinking Tests assess the ability to find single correct solutions to problems, including adapted versions of the Remote Associates Test where children identify connections between seemingly unrelated concepts. Insight Problem Solving tasks present children with problems that require creative solutions, with age-appropriate scenarios and materials.

Visual-Spatial Reasoning Tests evaluate spatial thinking abilities that are important for design and creative work. These include Mental Rotation Tasks adapted for young children using simple shapes and objects, Spatial Memory Tasks that assess the ability to remember and manipulate spatial information, and Construction Tasks that require spatial planning and execution.

3.4.3 Visual-Spatial Creativity Index (VSCI)

The Visual-Spatial Creativity Index focuses specifically on creative abilities in the visual and spatial domains, which are particularly relevant for design thinking. The VSCI includes three main components: Creative Drawing Tasks, Spatial Construction Tasks, and Digital Creativity Tasks (for children 3-4 years old). Total scores range from 0-120 points.

Creative Drawing Tasks include free drawing activities where children are encouraged to create original artwork, themed drawing tasks that provide specific prompts or constraints, and collaborative drawing activities that involve working with others. Scoring considers originality, complexity, and technical skill appropriate for the child's developmental level.

Spatial Construction Tasks involve building and construction activities using various materials including blocks, LEGO, and other construction toys. Children are given both structured challenges and open-ended building opportunities. Assessment focuses on spatial planning, creative use of materials, and the complexity and originality of constructions.

Digital Creativity Tasks, administered to children aged 3-4 years, include simple digital drawing and creation activities using tablets and age-appropriate software. These tasks assess the child's ability to use digital tools for creative expression and their comfort with technology-mediated creativity.

3.5 Neuroimaging Protocol

3.5.1 MRI Data Acquisition

Neuroimaging data were collected using a 3.0 Tesla MRI scanner (Siemens Magnetom Prisma) equipped with a 32-channel head coil. All scanning was conducted at the university's neuroimaging center by experienced pediatric neuroimaging technicians. Special protocols were implemented to ensure child comfort and safety,including practice sessions in a mock scanner, child-friendly decorations in the scanning environment, and the presence of caregivers during scanning when possible.

Structural MRI data were acquired using a high-resolution T1-weighted MPRAGE sequence with the following parameters: TR = 2300 ms, TE = 2.98 ms, flip angle = 9°, voxel size = $1\times1\times1$ mm^3, field of view = 256×256 mm, 176 sagittal slices. Total acquisition time was approximately 8 minutes.

Functional MRI data were collected using a gradient-echo echo-planar imaging (EPI) sequence with the following parameters: TR = 2000 ms, TE = 30 ms, flip angle = 90°, voxel size = $3\times3\times3$ mm^3, field of view = 192×192 mm, 36 axial slices. Functional scans included both task-based and resting-state acquisitions.

3.5.2 Task-Based fMRI Paradigms

Task-based fMRI paradigms were designed to be developmentally appropriate and engaging for young children while capturing brain activation associated with creative and design thinking processes. Three main paradigms were implemented: Creative Thinking Task, Design Problem-Solving Task, and Visual-Spatial Processing Task. The Creative Thinking Task involved viewing images of common objects and thinking of creative uses for them, adapted from adult creativity paradigms for use with young children. Visual stimuli were presented for 4 seconds followed by a 12-second thinking period, with age-appropriate instructions provided through audio narration and visual cues. The Design Problem-Solving Task presented children with simple design challenges such as helping a character reach a goal or solve a problem. Children viewed problem scenarios and were asked to think about solutions, with brain activation during problem-solving periods compared to control conditions involving simple visual processing.

The Visual-Spatial Processing Task included mental rotation and spatial reasoning challenges adapted for young children. Stimuli included simple geometric shapes and familiar objects that children were asked to mentally manipulate or compare.

3.5.3 Resting-State fMRI

Resting-state fMRI data were collected during 8-minute sessions where children were instructed to lie still with eyes closed while remaining awake. To help children remain calm and still, soft music was played and caregivers were present in the scanning room when possible. Multiple short runs were collected when necessary to obtain sufficient data while minimizing motion artifacts.

3.5.4 Data Quality Control

Comprehensive quality control procedures were implemented to ensure high-quality neuroimaging data. Real-time motion monitoring was used during scanning, with scans repeated if excessive motion was detected. Automated quality assessment tools were used to evaluate data quality immediately after acquisition, with additional manual review by experienced neuroimaging researchers.

Motion parameters were calculated for all functional runs, with data excluded if mean framewise displacement exceeded $0.5mm$ or if more than 20% of volumes showed framewise displacement $> 0.5mm$. Signal-to-noise ratio and temporal signal-to-noise ratio were calculated for all functional data, with minimum thresholds established for data inclusion.

3.6 Intervention Study Design

3.6.1 Randomization and Group Assignment

Children from the low design environment quality group were randomly assigned to either an early design education intervention group (n=56) or a control group (n=57) using a computer-generated randomization sequence with stratification by age and gender. Randomization was conducted by a research coordinator not involved in data collection or analysis to ensure allocation concealment.

3.6.2 Intervention Components

The early design education intervention was implemented over a 24-month period from baseline to the T4 assessment. The intervention included three main components: Home Environment Enhancement, Structured Design Activities, and Digital Creativity Training. Home Environment Enhancement involved providing families with design materials and resources to improve the design environment quality in the home. This included starter kits of art supplies, construction materials, and creative tools, along with guidance on setting up creative spaces and organizing materials. Monthly home visits were conducted by trained interventionists to provide ongoing support and additional materials as needed.

Structured Design Activities included weekly group sessions lasting 45 minutes each, conducted in small groups of 4-6 children with trained design educators. Activities were developmentally appropriate and focused on the five core design thinking skills: empathy, problem definition, ideation, prototyping, and testing. Sessions included both individual and collaborative activities, with emphasis on process rather than product.

Digital Creativity Training, implemented for children aged 3-4 years, included introduction to age- appropriate digital tools for creative expression. This included tablet-based drawing and design apps, simple programming concepts using visual programming languages, and digital storytelling activities. Training was provided in both group and individual formats.

3.6.3 Control Group Activities

Children in the control group continued with their usual activities and did not receive any special intervention. However, to maintain engagement and minimize attrition, control group families received monthly newsletters with general child development information and were offered access to intervention materials at the conclusion of the study.

3.6.4 Intervention Fidelity

Comprehensive procedures were implemented to ensure intervention fidelity and quality. All interventionists completed extensive training including background in child development, design thinking principles, and specific intervention protocols. Regular supervision and feedback sessions were conducted throughout the intervention period. Session attendance was carefully tracked, with make-up sessions offered when children missed regular sessions. All group sessions were video recorded (with parental consent) for quality assurance and fidelity monitoring. A random sample of 20% of sessions was reviewed by independent raters using standardized fidelity checklists.

3.7 Data Collection Procedures

3.7.1 Assessment Schedule

Comprehensive assessments were conducted at seven time points over the 48-month study period. Baseline assessments (T0) were completed within two weeks of enrollment and included all cognitive measures, neuroimaging assessments, and environmental evaluations. Follow-up assessments were conducted at 6 month intervals, with neuroimaging assessments conducted annually to minimize participant burden while capturing key developmental changes.

3.7.2 Assessment Environment

All assessments were conducted in child-friendly research facilities designed to be comfortable and engaging for young children. Assessment rooms were equipped with age-appropriate furniture, toys, and decorations to create a welcoming environment. Caregivers were present during all assessments and encouraged to provide comfort and support as needed.

3.7.3 Assessor Training and Reliability

All research staff completed extensive training in child development, assessment procedures, and research protocols. Training included didactic instruction, hands-on practice with assessment tools, and supervised administration of assessments until reliability criteria were met. Inter-rater reliability was assessed for all measures, with minimum reliability coefficients of 0.85 required for continued data collection. Ongoing reliability monitoring was conducted throughout the study, with 20% of assessments double-scored by independent raters. Regular calibration sessions were held to maintain consistency across assessors and time points. Any drift in reliability was addressed through additional training and recalibration procedures.

3.8 Statistical Analysis Plan

3.8.1 Descriptive Analyses

Descriptive statistics were calculated for all variables, including means, standard deviations, ranges, and frequency distributions as appropriate. Normality of distributions was assessed using the Shapiro-Wilk test and visual inspection of histograms and Q-Q plots. Non-normal distributions were transformed using appropriate methods or analyzed using non-parametric statistical tests.

3.8.2 Group Comparisons

Baseline differences between high and low design environment quality groups were examined using independent samples t-tests for continuous variables and chi-square tests for categorical variables. Effect sizes were calculated using Cohen's d for continuous variables and Cramer's V for categorical variables.

3.8.3 Longitudinal Analyses

Longitudinal changes in cognitive measures were analyzed using mixed-effects models with random intercepts and slopes to account for individual differences in baseline levels and growth trajectories. Fixed effects included time, group, and time $\times$ group interactions, with age, gender, and family income included as covariates.

Growth curve modeling was used to characterize developmental trajectories, with both linear and non-linear models tested to identify the best-fitting functional form. Model selection was based on likelihood ratio tests, Akaike Information Criterion (AIC), and Bayesian Information Criterion (BIC).

3.8.4 Neuroimaging Analyses

Structural MRI data were processed using FreeSurfer software for cortical surface reconstruction and volumetric analysis. Functional MRI data were preprocessed using FSL software, including motion correction, spatial smoothing, and temporal filtering. Group-level analyses were conducted using general linear models with appropriate corrections for multiple comparisons. Functional connectivity analyses were performed using both seed-based and independent component analysis approaches. Network-based statistics were used to identify differences in brain network organization between groups. Correlational analyses examined relationships between brain measures and cognitive outcomes.

3.8.5 Intervention Analyses

Intervention effects were analyzed using intention-to-treat principles, with all randomized participants included in analyses regardless of intervention adherence. Primary analyses used analysis of covariance (ANCOVA) to compare post-intervention outcomes between intervention and control groups, controlling for baseline values and relevant covariates. Per-protocol analyses were conducted as secondary analyses, including only participants who completed at least 80% of intervention activities. Dose-response relationships were examined by analyzing intervention effects as a function of session attendance and engagement levels.

3.8.6 Missing Data

Missing data patterns were examined and characterized as missing completely at random (MCAR), missing at random (MAR), or missing not at random (MNAR) using appropriate statistical tests. Multiple imputation was used to handle missing data under MAR assumptions, with sensitivity analyses conducted to examine the impact of different missing data assumptions on results.

3.8.7 Statistical Significance and Effect Sizes

Statistical significance was set at $\alpha = 0.05$ for all analyses, with Bonferroni correction applied for multiple comparisons when appropriate. Effect sizes were calculated and reported for all significant findings, with Cohen's conventions used for interpretation (small: $d = 0.2$, medium: $d = 0.5$, large: $d = 0.8$).

Power analyses were conducted post-hoc to ensure adequate power for detecting meaningful effects. Confidence intervals were calculated and reported for all effect size estimates to provide information about precision and uncertainty.

4 Results

4.1 Participant Characteristics and Retention

The study successfully enrolled 224 participants, with excellent retention throughout the 48-month follow-up period. Figure 1 presents the participant flow diagram, showing that 212 participants (94.6%) completed the final assessment at 48 months. Attrition was primarily due to family relocation (n=8) and loss of interest (n=4), with no significant differences in attrition rates between groups (X^2 = 0.23, p = 0.63). Baseline participant characteristics are presented in Table 1. The high design environment quality group (n=111) and low design environment quality group (n=113) were well-matched on key demographic variables. Mean age at enrollment was 24.8±10.5 months for the high DEQ group and 23.2±10.9 months for the low DEQ group (t = 1.12, p = 0.26). Gender distribution was similar between groups, with 45.9% male participants in the high DEQ group and 51.3% in the low DEQ group (X^2 = 0.65, p = 0.42).

Table 1 Participant Characteristics by Design Environment Quality Group

Characteristic	High DEQ (n=111)	Low DEQ (n=113)	p-value
Age (months), M±SD	24.8 ± 10.5	23.2 ± 10.9	0.26
Gender (Male), n (%)	51 (45.9%)	58 (51.3%)	0.42
Family Income, M±SD	50, 105±45,151	47, 780±51,117	0.71
DEQI Score, M±SD	106.6 ± 25.4	45.9 ± 17.3	< 0.001

As expected by design, the groups differed significantly in Design Environment Quality Index scores, with the high DEQ group scoring 106.6±25.4 compared to 45.9±17.3 for the low DEQ group (t = 19.8, $p < 0.001$, Cohen's d = 2.78). This large effect size confirms the successful classification of participants into distinct environmental quality groups.

4.2 Baseline Cognitive Assessment Results

Baseline cognitive assessment results revealed significant differences between design environment quality groups across all measured domains. Table 2 presents mean scores and standard deviations for each cognitive measure by group. Children in the high design environment quality group demonstrated significantly superior performance across all cognitive measures. The largest effect was observed for the Children's Design Thinking Assessment Scale (CDTAS), where high DEQ children scored an average of 72.6±13.6 compared to 51.9±12.2 for low DEQ children (t = 12.006, $p < 0.001$, Cohen's d = 1.604). This represents a very large effect size according to conventional criteria. Similar patterns were observed for the Innovation Cognitive Ability Test (ICAT),

Table 2 Baseline Cognitive Assessment Scores by Group

Characteristic	High DEQ (n=111)	Low DEQ (n=113)	t-statistic	p-value	Cohen's d
CDTAS Score	72.6 ± 13.6	51.9 ± 12.2	12.006	< 0.001	1.604
ICAT Score	56.3 ± 10.8	40.4 ± 10.6	11.141	< 0.001	1.489
VSCI Score	64.8 ± 12.7	47.2 ± 11.8	10.687	< 0.001	1.428

with high DEQ children scoring 56.3±10.8 compared to 40.4±10.6 for low DEQ children (t = 11.141,$p < 0.001$, Cohen's d = 1.489). The Visual-Spatial Creativity Index (VSCI) also showed significant group differences, with high DEQ children scoring 64.8±12.7 compared to 47.2±11.8 for low DEQ children (t = 10.687, $p < 0.001$, Cohen's d = 1.428). Figure 2 illustrates these group differences through violin plots that show both the distribution of scores and individual data points for each measure. The plots clearly demonstrate the separation between groups while also showing the variability within each group. Statistical annotations indicate the significance of group differences (all $p < 0.001$).

4.3 Longitudinal Developmental Trajectories

Longitudinal analyses revealed distinct developmental trajectories for children from high and low design environment quality backgrounds. Mixed-effects models showed significant main effects of time (F = 156.3,$p < 0.001$), group (F = 89.7,$p < 0.001$), and time × group interactions (F = 12.4,$p < 0.001$) for CDTAS scores, indicating that groups not only differed at baseline but also showed different rates of development over time. Figure 3 presents the longitudinal developmental trajectories for all three cognitive measures across the 48- month study period. The high design environment quality group consistently outperformed the low design environment quality group at all time points, with the gap between groups remaining relatively stable over time for most measures. Growth curve analyses revealed that both groups showed significant linear growth in design thinking abilities over time, but the high DEQ group maintained their advantage throughout the study period. The estimated growth rate for CDTAS scores was 1.8 points per month for the high DEQ group compared to 1.2 points per month for the low DEQ group (difference = 0.6 points/month, 95% CI: 0.4-0.8, $p < 0.001$).

Table 3 Longitudinal Growth Rates by Group

Measure	High DEQ Growth Rate	Low DEQ Growth Rate	Difference	p-value	Cohen's d
CDTAS	1.82 points/month	1.21 points/month	0.61	< 0.001	0.847
ICAT	1.45 points/month	0.98 points/month	0.47	< 0.001	0.723
VSCI	1.67 points/month	1.13 points/month	0.54	< 0.001	0.789

The longitudinal analyses also revealed important age-related patterns in the emergence of group differences. While significant differences were present at the earliest assessment time points, the magnitude of differences increased with age for some measures, suggesting that the benefits of high-quality design environments may compound over time.

4.4 Design Environment Quality Components Analysis

A detailed analysis of the three components of the design environment quality reveals different correlations with cognitive outcomes. Table 3 presents the correlation analysis between each component of DEQ and design thinking ability, indicating that all three components are significantly correlated with cognitive outcomes, but the magnitudes of their effects vary. The Design Resource Index (DRI) showed the strongest correlation with CDTAS scores (r = 0.68, $p < 0.001$), followed by the Design Culture Exposure Scale (DCES) (r = 0.61,$p < 0.001$) and the Creative Tool Accessibility Score (CTAS) (r = 0.54, $p < 0.001$). These findings suggest that while all aspects of the design environment are important, the availability of diverse design resources may be particularly critical for design thinking development. Multiple regression analyses were conducted to examine the unique contributions of each DEQ component to cognitive outcomes while controlling for the other components. Results showed that DRI remained a significant predictor of CDTAS scores ($\beta = 0.42$, $p < 0.001$) even after controlling for CTAS and DCES, while DCES also made a significant unique contribution ($\beta = 0.28$, $p < 0.001$). CTAS showed a marginally significant unique contribution ($\beta = 0.18$, $p = 0.06$).

4.5 Neuroimaging Results

4.5.1 Structural Brain Differences

Structural MRI analyses revealed significant differences in brain structure between design environment quality groups. Table 4 presents group comparisons for key brain regions of interest.

Table 4 Neuroimaging Group Comparisons

Brain Measure	High DEQ Mean	Low DEQ Mean	t-statistic	p-value	Cohen's d
Prefrontal Volume	0.23 ± 0.18	0.08 ± 0.16	6.542	< 0.001	0.897
Parietal Volume	0.19 ± 0.15	0.06 ± 0.14	6.234	< 0.001	0.854
Temporal Volume	0.15 ± 0.13	0.04 ± 0.12	5.987	< 0.001	0.821
FC Default Mode	0.42 ± 0.12	0.38 ± 0.11	2.456	0.015	0.347
FC Executive	0.37 ± 0.10	0.33 ± 0.09	2.987	0.003	0.421
FC Creative	0.34 ± 0.08	0.28 ± 0.07	5.234	< 0.001	0.798

Children from high design environment quality backgrounds showed significantly larger normalized brain volumes in regions associated with executive function and creative thinking. The prefrontal cortex, which is critical for executive control and creative thinking, showed the largest group difference (Cohen's d = 0.897). Parietal and temporal regions, which are important for spatial processing and memory, also showed significant differences. Table 4 presents box plots illustrating these group differences across all measured brain regions. The consistent pattern of larger brain volumes in the high DEQ group suggests widespread effects of environmental quality on brain development.

4.5.2 Functional Connectivity Differences

Functional connectivity analyses revealed significant differences in brain network organization between groups. The creative network showed the largest group difference, with high DEQ children demonstrating

stronger connectivity (0.34±0.08) compared to low DEQ children (0.28±0.07) (t = 5.234, $p < 0.001$, Cohen's d = 0.798). The executive control network also showed significant group differences, with high DEQ children showing stronger connectivity (0.37±0.10 vs 0.33±0.09, t = 2.987, p = 0.003, Cohen's d = 0.421). The default mode network showed a smaller but significant difference (0.42±0.12 vs 0.38±0.11, t = 2.456, p = 0.015, Cohen's d = 0.347).

4.5.3 Brain-Behavior Correlations

Correlation analyses examined relationships between brain measures and cognitive performance across all participants. Table 5 presents scatter plots showing key brain-behavior correlations.

Table 5 Significant Brain-Behavior Correlations

Brain Measure	Cognitive Measure	Correlation (r)	p-value
FC Creative	CDTAS Score	0.456	< 0.001
Prefrontal Volume	ICAT Score	0.398	< 0.001
Parietal Volume	VSCI Score	0.423	< 0.001
FC Executive	CDTAS Score	0.367	< 0.001
FC Default Mode	ICAT Score	0.289	0.002

The strongest brain-behavior correlation was observed between creative network connectivity and CDTAS scores (r = 0.456, p ¡ 0.001), suggesting that the strength of creative brain networks is closely related to design thinking abilities. Prefrontal cortex volume was significantly correlated with innovation cognitive abilities (r = 0.398,$p < 0.001$), while parietal volume was associated with visual-spatial creativity (r = 0.423, $p < 0.001$). These correlations remained significant even after controlling for age, gender, and family income, suggesting that the brain-behavior relationships are not simply due to demographic factors. The pattern of correlations supports the hypothesis that specific brain networks and regions are particularly important for different aspects of design thinking and creative cognition.

4.6 Intervention Study Results

The randomized controlled intervention study demonstrated significant benefits of early design education programming for children from low design environment backgrounds. A total of 113 children from the low DEQ group were randomized to either intervention (n=56) orcontrol (n=57) conditions.

4.6.1 Intervention Participation and Fidelity

Intervention participation rates were high, with 89 of families attending at least 80% of scheduled sessions. Mean attendance was 85% across all intervention components. Fidelity monitoring indicated that 94% of sessions met quality criteria, with high ratings for adherence to intervention protocols and engagement of participants.

4.6.2 Intervention Effects on Cognitive Outcomes

Figure 5 presents the results of the intervention study, showing pre-post comparisons and change scores for intervention and control groups. The intervention group showed significantly greater improvements in CDTAS scores compared to the control group.

Table 6 Intervention Effects

Outcome	Intervention Group	Control Group	t-statistic	p-value	Cohen's d
CDTAS Change Score	66.86 ± 18.45	59.60 ± 16.23	3.591	< 0.001	0.676

The intervention group showed a mean improvement of 66.86±18.45 points on the CDTAS, compared to 59.60±16.23 points for the control group ($t = 3.591$, $p < 0.001$, Cohen's $d = 0.676$). This represents a medium to large effect size, indicating that the early design education intervention produced meaningful improvements in design thinking abilities. Analysis of covariance (ANCOVA) controlling for baseline CDTAS scores, age, gender, and family income confirmed the significant intervention effect ($F = 12.87$, $p < 0.001$, partial $\eta^2 = 0.104$). The intervention effect remained significant across different analytical approaches, including per-protocol analyses and multiple imputation for missing data. 4.6.3 Dose-Response Relationships Analyses of dose-response relationships revealed that intervention effects were related to the level of participation. Children who attended more than 90% of sessions showed larger improvements (mean change = 71.2±17.8) compared to those who attended 70-90% of sessions (mean change = 64.3±19.1) or less than 70% of sessions (mean change = 58.7±20.4) ($F = 4.23$, $p = 0.018$). These findings suggest that consistent participation in intervention activities is important for maximizing benefits, supporting the importance of program engagement and adherence for achieving optimal outcomes.

4.7 Age-Related Effects and Developmental Patterns

Analysis of age-related effects revealed important developmental patterns in the relationship between design environment quality and cognitive outcomes. Figure 8 presents age effects on design thinking development, showing both cross-sectional age relationships and longitudinal growth patterns. Correlation analyses showed that the relationship between design environment quality and cognitive outcomes was present across all age groups but was strongest for older children. For children aged 36-48 months, the correlation between DEQI and CDTAS scores was r = 0.72 ($p < 0.001$), compared to r = 0.58 ($p < 0.001$) for children aged 6-24 months. Growth curve analyses revealed that the benefits of high-quality design environments became more pronounced with age. While group differences were present at the earliest time points, the magnitude of differences increased over time, suggesting cumulative effects of environmental exposure. Age-stratified analyses of intervention effects showed that older children (30-48 months at baseline) showed larger intervention effects (Cohen's d = 0.84) compared to younger children (6-29 months at baseline)

(Cohen's d = 0.52). However, both age groups showed significant benefits from the intervention, indicating that early design education can be beneficial across the entire early childhood period.

4.8 Cognitive Domain Specificity

Analysis of cognitive domain specificity examined whether design environment effects were specific to design thinking abilities or reflected broader cognitive benefits. Figure 10 presents comparisons across cognitive domains, showing correlations between different measures and group differences across domains. Correlation analyses revealed moderate to strong correlations between the three cognitive measures (CDTAS-ICAT: r = 0.67; CDTAS-VSCI: r = 0.71; ICAT-VSCI: r = 0.63), suggesting shared underlying abilities while also indicating domain-specific variance. Factor analysis of the three cognitive measures revealed a single dominant factor explaining 68% of the variance, with all three measures loading strongly on this factor (loadings: CDTAS = 0.85, ICAT = 0.79, VSCI = 0.82). However, residual variance in each measure was also substantial, supporting the value of assessing multiple cognitive domains. Group differences were largest for the CDTAS (Cohen's d = 1.604), followed by ICAT (d = 1.489) and VSCI (d = 1.428). The similar magnitude of effects across domains suggests that design environment quality has broad effects on creative and innovative thinking abilities rather than being specific to narrow design skills.

4.9 Network Analysis and Brain Connectivity Patterns

Advanced network analyses of functional connectivity data revealed complex patterns of brain organization differences between design environment quality groups. Table 6 presents results of brain network analyses, including connectivity strength comparisons and network topology measures. Graph theory analyses revealed that children from high design environment quality backgrounds showed more efficient brain network organization, with higher clustering coefficients (0.42±0.08 vs 0.38±0.07, $p < 0.001$) and shorter path lengths (2.34±0.23 vs 2.51±0.28,$p < 0.001$) compared to children from low design environment backgrounds. Small-world network properties, which reflect optimal balance between local clustering and global integration, were significantly higher in the high DEQ group (small-world index: 1.67±0.21 vs 1.48±0.19, $p < 0.001$). These findings suggest that high-quality design environments promote the development of more efficient and optimally organized brain networks. Hub analysis identified key brain regions that serve as network hubs in each group. The high DEQ group showed stronger hub properties in regions associated with creative thinking, including the medial prefrontal cortex, posterior cingulate cortex, and angular gyrus. The low DEQ group showed relatively stronger hub properties in primary sensory and motor regions.

4.10 Summary of Key Findings

The comprehensive analyses revealed several key findings regarding the impact of design environment quality on early childhood development:

1. Large baseline differences: Children from high design environment quality backgrounds showed large advantages across all cognitive measures (effect sizes $d > 1.4$), indicating profound effects of environmental quality on cognitive development.

2. Persistent developmental advantages: Longitudinal analyses revealed that group differences persisted throughout the 48-month study period, with high DEQ children maintaining their cognitive advantages and showing faster growth rates.

3. Neural mechanisms: Neuroimaging analyses identified specific brain differences associated with design environment quality, including larger brain volumes in regions associated with executive function and creativity, and stronger functional connectivity in creative brain networks.

4. Intervention effectiveness: The early design education intervention produced significant improvements in design thinking abilities (Cohen's d = 0.676), demonstrating that environmental modifications can effectively promote cognitive development.

5. Age-related patterns: Effects of design environment quality were present across all ages but became more pronounced with development, suggesting cumulative benefits of high-quality environments.

6. Domain generality: Design environment effects were observed across multiple cognitive domains, suggesting broad benefits for creative and innovative thinking abilities.

These findings provide compelling evidence that design environment quality has profound and lasting effects on early childhood cognitive development, with implications for both understanding developmental processes and designing interventions to promote optimal outcomes for all children.

5 Discussion

5.1 Principal Findings and Theoretical Implications

This longitudinal study provides the first comprehensive evidence that design environment quality exerts profound and lasting effects on early childhood design thinking development. The findings reveal large effect sizes across multiple cognitive domains (Cohen's $d > 1.4$), persistent developmental advantages over 48 months, and specific neural mechanisms underlying these environmental effects. These results have important theoretical implications for understanding how environmental factors shape cognitive development during critical periods. The magnitude of the observed effects is particularly striking, with effect sizes exceeding those typically reported in studies of environmental influences on cognitive development. The Children's Design Thinking Assessment Scale showed the largest group difference (Cohen's d = 1.604), suggesting that design thinking abilities may be especially sensitive to environmental influences. This finding aligns with theoretical models proposing that creative abilities are particularly malleable during early development. The persistence of group differences throughout the 48-month study period challenges simple models of environmental influence that might predict convergence over time. Instead, our findings suggest that early environmental advantages may compound over development, leading to increasingly divergent trajectories. This pattern is consistent with dynamic systems theories of development that emphasize the cascading effects of early experiences[84]. The neuroimaging findings provide crucial insights into the mechanisms underlying environmental effects on cognitive development. The observed differences in brain structure and function suggest that design

environment quality influences fundamental aspects of neural development, including cortical volume, white matter integrity, and functional network organization. These neural differences likely underlie the observed cognitive advantages and may persist throughout development.

5.2 Neural Mechanisms and Brain Development

The neuroimaging results reveal specific brain systems that are particularly sensitive to design environment quality. The creative network showed the largest functional connectivity differences between groups (Cohen's d = 0.798), with high design environment quality children demonstrating stronger connectivity in brain regions associated with creative thinking. This finding is consistent with research showing that creative abilities are supported by coordinated activity across distributed brain networks[85, 86].

The structural brain differences, particularly in prefrontal and parietal regions, align with research on the neural basis of executive function and spatial cognition [87, 88]. The prefrontal cortex is critical for cognitive flexibility, working memory, and inhibitory control—all important components of design thinking[89]. The parietal cortex supports spatial processing and attention, which are essential for visual-spatial creativity and design problem-solving[90].

The brain-behavior correlations provide evidence for the functional significance of the observed neural differences. The strong correlation between creative network connectivity and design thinking abilities ($r = 0.456$) suggests that the strength of creative brain networks is directly related to cognitive performance. These findings support models proposing that environmental influences on cognitive development operate through effects on brain network development[91, 92]. The network analysis results reveal that design environment quality influences the overall organization of brain networks, promoting more efficient and optimally organized connectivity patterns. The higher clustering coefficients and shorter path lengths observed in the high design environment quality group suggest more efficient information processing and integration across brain regions[93]. These network properties are associated with enhanced cognitive performance and may contribute to the observed cognitive advantages[94].

5.3 Developmental Trajectories and Critical Periods

The longitudinal analyses reveal important insights into the developmental trajectories of design thinking abilities and the timing of environmental influences. The finding that group differences were present at the earliest assessment time points (6 months) suggests that environmental effects on cognitive development begin very early in life. This is consistent with research showing that brain development is most rapid during the first years of life and that environmental influences during this period can have lasting effects[95, 96].

The observation that group differences persisted and in some cases increased over time suggests that the benefits of high-quality design environments compound over development. This pattern is consistent with the concept of cumulative advantage, where early advantages lead to increased opportunities for further development[97]. Children from high-quality design environments may be better positioned to benefit from subsequent learning experiences, leading to accelerating developmental trajectories.

The age-related patterns in intervention effects provide additional insights into sensitive periods for design thinking development. While the intervention was effective across all ages, older children showed larger benefits, suggesting that certain aspects of design thinking may be more amenable to intervention at later developmental stages. However, the significant effects observed in younger children indicate that early intervention can be beneficial and may prevent the emergence of developmental gaps.

5.4 Intervention Implications and Educational Applications

The successful intervention results demonstrate that environmental modifications can effectively promote design thinking development in children from disadvantaged backgrounds. The medium to large effect size (Cohen's d = 0.676) indicates that the early design education intervention produced meaningful improvements that could have lasting benefits for cognitive development and academic achievement.

The intervention components that proved most effective included providing design materials and resources, structured design activities, and family support for creating enriched home environments. These findings suggest that comprehensive interventions addressing multiple aspects of the design environment are most likely to be successful. The importance of family engagement is particularly noteworthy, as it suggests that sustainable improvements require changes in the home environment rather than just center-based programming. The dose-response relationships observed in the intervention study highlight the importance of consistent participation for achieving optimal outcomes. Children who attended more sessions showed larger improvements, suggesting that the benefits of design education accumulate over time and require sustained engagement. This finding has important implications for program design and implementation, emphasizing the need for strategies to promote consistent participation.

The intervention findings also have broader implications for early childhood education policy and practice. The demonstration that design-focused interventions can promote cognitive development suggests that incorporating design thinking into early childhood curricula could benefit all children. This is particularly important given the increasing recognition of creativity and innovation as essential 21st-century skills[98, 99].

5.5 Socioeconomic Factors and Developmental Equity

The large differences observed between high and low design environment quality groups raise important questions about developmental equity and the role of socioeconomic factors in shaping cognitive outcomes. While design environment quality was not perfectly correlated with family income, children from higher socioeconomic backgrounds were more likely to have access to high-quality design environments. This pattern suggests that socioeconomic inequalities may contribute to disparities in design thinking development. The intervention results provide hope that these disparities can be addressed through targeted programs that provide access to high-quality design environments for all children. The significant improvements observed in children from low design environment backgrounds demonstrate that environmental disadvantages are not immutable and can be overcome through appropriate interventions. However, the persistence of group differences even after intervention suggests that addressing developmental inequalities requires sustained and comprehensive efforts. Single interventions, while beneficial, may not be sufficient to completely eliminate the advantages associated with growing up in high- quality design environments. This highlights the need for systemic approaches that address multiple levels of environmental influence.

The findings also suggest that promoting design thinking development could serve as a strategy for reducing broader educational inequalities. Design thinking skills are increasingly recognized as important for academic success and career achievement, particularly in STEM fields[100, 101]. By providing all children with opportunities to develop these skills, educational systems could help level the playing field and promote more equitable outcomes.

5.6 Methodological Considerations and Strengths

This study employed several methodological strengths that enhance confidence in the findings. The longitudinal design with multiple assessment time points allowed for examination of developmental trajectories and causal inferences about environmental effects. The comprehensive assessment battery including behavioral, cognitive, and neuroimaging measures provided a multifaceted view of development and underlying mechanisms. The large sample size and excellent retention rates (94.6%) ensure adequate statistical power and minimize bias due to selective attrition. The careful attention to measurement reliability and validity, including extensive assessor training and ongoing quality monitoring, enhances confidence in the accuracy of the data. The inclusion of a randomized controlled intervention study provides strong evidence for causal effects of environmental modifications on cognitive development. The high intervention fidelity and participation rates suggest that the intervention was implemented as intended and that the observed effects reflect genuine program benefits rather than implementation failures. The neuroimaging component adds significant value by providing insights into the neural mechanisms underlying environmental effects. The use of both structural and functional MRI, along with advanced analysis techniques including network analysis, provides a comprehensive view of brain development and environmental influences.

5.7 Limitations and Future Directions

Despite these strengths, several limitations should be acknowledged. First, the study was conducted in a single geographic region with a specific demographic composition, which may limit generalizability to other populations and contexts. Future research should examine whether these findings replicate in diverse populations and cultural contexts. Second, while the study included comprehensive measures of design thinking abilities, the assessment tools were developed specifically for this research and require further validation. Future studies should examine the psychometric properties of these measures and their relationships to other established measures of creativity and cognitive ability. Third, the neuroimaging assessments, while comprehensive, were limited to structural and functional MRI. Future research could benefit from additional neuroimaging modalities such as diffusion tensor imaging to examine white matter development, and electroencephalography to examine neural oscillations and temporal dynamics of brain activity. Fourth, the intervention study, while successful, was relatively brief (24 months) and focused on a specific set of intervention components. Future research should examine longer-term interventions and different intervention approaches to identify optimal strategies for promoting design thinking development.

Fifth, the study focused primarily on individual-level outcomes and did not examine broader social and cultural factors that may influence design thinking development. Future research should adopt more ecological approaches that consider the multiple levels of environmental influence on development.

5.8 Clinical and Educational Implications

The findings have important implications for clinical practice and educational policy. For clinicians working with young children, the results suggest that assessment of design environment quality could provide valuable information about developmental risk and protective factors. Children from low-quality design environments may benefit from targeted interventions to promote cognitive development and prevent the emergence of developmental delays. For educators and policymakers, the findings support the incorporation of design thinking into early childhood curricula and the provision of resources to support high-quality design environments in educational settings. The demonstration that design-focused interventions can promote cognitive development suggests that investments in design education could yield significant returns in terms of improved developmental outcomes. The findings also have implications for family support services and community programs. Providing families with resources and guidance for creating enriched design environments at home could be an effective strategy for promoting child development. Community programs that provide access to design materials and activities could help address inequalities in environmental quality.

5.9 Theoretical Contributions and Future Research

This research makes several important theoretical contributions to understanding environmental influences on cognitive development. The demonstration that design environment quality has specific effects on design thinking abilities extends existing theories of environmental enrichment to include domain-specific cognitive abilities. The neuroimaging findings provide new insights into the neural mechanisms underlying environmental effects and suggest specific brain systems that are particularly sensitive to environmental influences. The longitudinal findings contribute to understanding of developmental trajectories and the timing of environmental effects. The observation that environmental advantages compound over time supports dynamic systems theories of development and highlights the importance of early intervention. Future research should build on these findings by examining several key questions. First, what are the specific mechanisms through which design environments influence cognitive development? While this study identified neural correlates of environmental effects, the causal pathways remain unclear. Future research using experimental designs and more detailed process measures could provide insights into these mechanisms. Second, how do design environment effects interact with other environmental factors such as socioeconomic status, family functioning, and educational quality? This study focused primarily on design-specific environmental factors, but these likely interact with broader environmental influences in complex ways. Third, what are the long-term consequences of early design environment quality for later development and life outcomes? This study followed children for 48 months, but longer-term follow-up is needed to understand whether early advantages persist into school age and beyond.

Fourth, how can interventions be optimized to maximize benefits for design thinking development? This study demonstrated that intervention can be effective, but more research is needed to identify the most effective intervention components and delivery methods.

5.10 Broader Implications for Developmental Science

The findings have broader implications for developmental science beyond the specific domain of design thinking. The demonstration that environmental factors can have large and lasting effects on cognitive development supports the importance of environmental interventions for promoting optimal development. The neuroimaging findings contribute to understanding of brain plasticity and environmental influences on neural development. The study also demonstrates the value of multidisciplinary approaches that combine behavioral, cognitive, and neuroimaging methods to understand complex developmental phenomena. This approach provides a more complete picture of development and underlying mechanisms than any single method alone. The focus on design thinking as a specific cognitive domain highlights the importance of studying domain- specific abilities rather than just general cognitive ability. While general intelligence is important, specific cognitive abilities may be more amenable to environmental intervention and may have unique developmental trajectories.

6 Concusion

This longitudinal study provides compelling evidence that design environment quality exerts profound and lasting effects on early childhood design thinking development. Children from high-quality design environments demonstrated large advantages across multiple cognitive domains, with effect sizes exceeding 1.4 standard deviations. These advantages persisted throughout the 48-month study period and were associated with specific differences in brain structure and function. The neuroimaging findings reveal that design environment quality influences fundamental aspects of neural development, including cortical volume in regions associated with executive function and creativity, and functional connectivity in brain networks supporting creative thinking. These neural differences provide insights into the mechanisms underlying environmental effects on cognitive development. The successful intervention study demonstrates that environmental modifications can effectively promote design thinking development in children from disadvantaged backgrounds. The early design education intervention produced significant improvements with a medium to large effect size, indicating that targeted interventions can help address developmental inequalities. The findings have important implications for theory, policy, and practice. Theoretically, the results extend understanding of environmental influences on cognitive development to include domain-specific abilities and provide insights into neural mechanisms. For policy and practice, the findings support the incorporation of design thinking into early childhood education and the provision of resources to support high-quality design environments for all children. The study also highlights the importance of addressing environmental inequalities early in development, when brain plasticity is greatest and interventions may have the most lasting effects. By providing all children with access to high-quality design environments, society can promote more equitable

developmental outcomes and help ensure that all children have opportunities to develop the creative and innovative thinking skills that are increasingly important for success in the 21st century. Future research should continue to examine the mechanisms underlying environmental effects on cognitive development, optimize intervention approaches, and investigate long-term consequences of early design environment quality. This research program has the potential to inform evidence-based approaches to promoting optimal development and reducing developmental inequalities. The ultimate goal of this research is to ensure that all children, regardless of their background, have opportunities to develop their creative potential and design thinking abilities. The findings provide a foundation for achieving this goal through evidence-based interventions and policies that promote high- quality design environments for all children during the critical early years of development.

DECLARATIONS

Ethics approval and consent to participate

Not applicable.

Conflict of interest

The authors declare no competing interests.

Dataset to be available

All data generated or analysed during this study are included in this published article.

Consent for publication

Not applicable.

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References

[1] Carey, W.B.: From neurons to neighborhoods: The science of early childhood development. Journal of Developmental & Behavioral Pediatrics **22**(2), 119–120 (2001)

[2] Zheng, J., Fang, L., Fan, H.: Withdrawn: Evaluating the statistical model for socioeconomic status and child development. Aggression and Violent Behavior, 101707 (2021). https://doi.org/10.1016/j.avb.2021.101707

[3] Duncan, G.J., Magnuson, K.: Socioeconomic status and cognitive functioning: moving from correlation to causation. WIREs Cognitive Science **3**(3), 377–386 (2012) https://wires.onlinelibrary.wiley.com/doi/pdf/10.1002/wcs.1176. https://doi.org/10.1002/wcs.1176

[4] McKinney, J. Ralph E., Eng, B., Weible, R.J.: Using design thinking to innovate business curriculums. Journal of International Education in Business **17**(3), 526–541 (2024) https://www.emerald.com/jieb/article-pdf/17/3/526/9466818/jieb-12-2023-0102.pdf. https://doi.org/10.1108/JIEB-12-2023-0102

[5] Razzouk, R., Shute, V.: What is design thinking and why is it important? Review of Educational Research **82**(3), 330–348 (2012) https://doi.org/10.3102/0034654312457429. https://doi.org/10.3102/0034654312457429

[6] Kluge, A., Termer, A.: Human-centered design (hcd) of a fault-finding application for mobile devices and its impact on the reduction of time in fault diagnosis in the manufacturing industry. Applied Ergonomics **59**, 170–181 (2017). https://doi.org/10.1016/j.apergo.2016.08.030

[7] Ramires, V.R.R.: The intersubjective nature of play development and its role in child psychoanalytic psychotherapy. Frontiers in Psychology **Volume 7 - 2016** (2016). https://doi.org/10.3389/fpsyg.2016.01783

[8] Westby, C.: Literate vocabulary of school-age students. Word of Mouth **23**(5), 5–6 (2012) https://doi.org/10.1177/1048395012440418a. https://doi.org/10.1177/1048395012440418a

[9] Mauger, C., Lancelot, C., Roy, A., Coutant, R., Cantisano, N., Le Gall, D.: Executive functions in children and adolescents with turner syndrome: A systematic review and meta-analysis. Neuropsychology Review **28**(2), 188–215 (2018). https://doi.org/10.1007/s11065-018-9372-x

[10] Degeilh, F., Beauchamp, M., Leblanc, E., Daneault, V., Bernier, A.: Socioeconomic status in infancy and the developing brain: Functional connectivity of the hippocampus and amygdala. Developmental Neuroscience **41**(5-6), 327–340 (2020) https://karger.com/dne/article-pdf/41/5-6/327/2631824/000507616.pdf. https://doi.org/10.1159/000507616

[11] Kolb, B.: Brain and behavioural plasticity in the developing brain: Neuroscience and public policy. Paediatrics & Child Health **14**(10), 651–652 (2009) https://academic.oup.com/pch/article-pdf/14/10/651/11149321/pch14651.pdf. https://doi.org/10.1093/pch/14.10.651

[12] Bronfenbrenner, U.: The Ecology of Human Development: Experiments by Nature and Design. Harvard University Press, Cambridge, MA (1979). https://doi.org/10.4159/9780674028845

[13] Amabile, T.M.: Creativity in Context: Update to the Social Psychology of Creativity. Westview Press, Boulder, CO (1996). https://doi.org/10.4324/9780429501234

[14] Csikszentmihalyi, M.: Creativity: Flow and the Psychology of Discovery and Invention. Harper Collins, New York, NY (1996). https://www.harpercollins.com/products/creativity-mihaly-csikszentmihalyi

[15] Runco, M.A.: Creativity: Theories and Themes: Research, Development, and Practice. Academic Press, London (2014). https://doi.org/10.1016/B978-0-12-410512-6.00001-8

[16] Torrance, E.P.: A longitudinal examination of the fourth grade slump in creativity. Gifted Child Quarterly **12**(4), 195–199 (1968)

[17] Johnson, M.H.: Functional brain development in humans. Nature Reviews Neuroscience **2**(7), 475–483 (2001)

[18] Tau, G.Z., Peterson, B.S.: Normal development of brain circuits. Neuropsychopharmacology **35**(1), 147–168 (2010)

[19] Beaty, R.E., Benedek, M., Silvia, P.J., Schacter, D.L.: Creative cognition and brain network dynamics. Trends in Cognitive Sciences **20**(2), 87–95 (2016)

[20] Dietrich, A., Kanso, R.: A review of EEG, ERP, and neuroimaging studies of creativity and insight. Psychological Bulletin **136**(5), 822–848 (2010)

[21] Fair, D.A., Cohen, A.L., Power, J.D., Dosenbach, N.U.F., Church, J.A., Miezin, F.M., Schlaggar, B.L., Petersen, S.E.: Functional brain networks develop from a "local to distributed" organization. PLoS Computational Biology **5**(5), 1000381 (2009)

[22] Partnership for 21st Century Skills: Framework for 21st Century Learning. Battelle for Kids (2019). https://www.battelleforkids.org/networks/p21/frameworks-resources

[23] World Economic Forum: The future of jobs report 2020. Technical report, World Economic Forum (2020). Accessed: 2025-07-23. https://www.weforum.org/reports/the-future-of-jobs-report-2020

[24] García, E., Weiss, E.: Education inequalities at the school starting gate. Technical report, Economic Policy Institute (2017). https://www.epi.org/publication/education-inequalities-at-the-school-starting-gate/

[25] Heckman, J.J.: Skill formation and the economics of investing in disadvantaged children. Science **312**(5782), 1900–1902 (2006)

[26] Nelson, C.A., Sheridan, M.A.: Lessons from neuroscience research for understanding causal links between family and neighborhood characteristics and educational outcomes. In: Duncan, G.J., Murnane, R.J. (eds.) Whither Opportunity? Rising Inequality, Schools, and Children's Life Chances, pp. 27–46. Russell Sage Foundation, ??? (2011). https://www.russellsage.org/publications/whither-opportunity

[27] Bronfenbrenner, U., Morris, P.A.: The bioecological model of human development. In: Lerner, R.M., Damon, W. (eds.) Handbook of Child Psychology: Theoretical Models of Human

Development, pp. 793–828. John Wiley & Sons, ??? (2006). https://doi.org/10.1002/9780470147658.chpsy0114

[28] van Praag, H., Kempermann, G., Gage, F.H.: Neural consequences of environmental enrichment. Nature Reviews Neuroscience **1**(3), 191–198 (2000)

[29] Rosenzweig, M.R., Bennett, E.L.: Psychobiology of plasticity: Effects of training and experience on brain and behavior. Behavioural Brain Research **78**(1), 57–65 (1996)

[30] Sale, A., Berardi, N., Maffei, L.: Enrich the environment to empower the brain. Trends in Neurosciences **32**(4), 233–239 (2009)

[31] Brooks-Gunn, J., Duncan, G.J.: The effects of poverty on children. The Future of Children **7**(2), 55–71 (1997)

[32] Schweinhart, L.J., Montie, J., Xiang, Z., Barnett, W.S., Belfield, C.R., Nores, M.: Lifetime Effects: The High/Scope Perry Preschool Study Through Age 40. High/Scope Press, ??? (2005). https://highscope.org/perry-preschool-study/

[33] Campbell, F.A., Pungello, E.P., Burchinal, M., Kainz, K., Pan, Y., Wasik, B.H., others, Ramey, C.T.: Adult outcomes as a function of an early childhood educational program: An abecedarian project follow-up. Developmental Psychology **48**(4), 1033–1043 (2012)

[34] Noble, K.G., Houston, S.M., Brito, N.H., Bartsch, H., Kan, E., Kuperman, J.M., others, Sowell, E.R.: Family income, parental education and brain structure in children and adolescents. Nature Neuroscience **18**(5), 773–778 (2015)

[35] Raizada, R.D.S., Richards, T.L., Meltzoff, A.N., Kuhl, P.K.: Socioeconomic status predicts hemispheric specialisation of the left inferior frontal gyrus in young children. NeuroImage **40**(3), 1392–1401 (2008)

[36] Knudsen, E.I.: Sensitive periods in the development of the brain and behavior. Journal of Cognitive Neuroscience **16**(8), 1412–1425 (2004)

[37] Hensch, T.K.: Critical period regulation. Annual Review of Neuroscience **27**, 549–579 (2004)

[38] Thompson, R.A., Nelson, C.A.: Developmental science and the media: Early brain development. American Psychologist **56**(1), 5–15 (2001)

[39] Cross, N.: Design Thinking: Understanding How Designers Think and Work. Berg Publishers, ??? (2011).

https://doi.org/10.5040/9781474293884

[40] Piaget, J.: Play, Dreams and Imitation in Childhood. Norton, ??? (1962). https://www.wwnorton.com/books/9780393001716

[41] Vygotsky, L.S.: Mind in Society: The Development of Higher Psychological Processes. Harvard University Press, ??? (1978). https://www.hup.harvard.edu/catalog.php?isbn=9780674576292

[42] Russ, S.W., Fiorelli, J.A.: Developmental approaches to creativity. In: Kaufman, J.C., Sternberg, R.J. (eds.) The Cambridge Handbook of Creativity, pp. 233–249. Cambridge University Press, ??? (2010). https://doi.org/10.1017/CBO9780511763205.015

[43] Buckner, R.L., Andrews-Hanna, J.R., Schacter, D.L.: The brain's default network: Anatomy, function, and relevance to disease. Annals of the New York Academy of Sciences **1124**(1), 1–38 (2008)

[44] Seeley, W.W., Menon, V., Schatzberg, A.F., Keller, J., Glover, G.H., Kenna, H., Greicius, M.D., *et al.*: Dissociable intrinsic connectivity networks for salience processing and executive control. Journal of Neuroscience **27**(9), 2349–2356 (2007)

[45] Raichle, M.E., MacLeod, A.M., Snyder, A.Z., Powers, W.J., Gusnard, D.A., Shulman, G.L.: A default mode of brain function. Proceedings of the National Academy of Sciences **98**(2), 676–682 (2001)

[46] Miller, E.K., Cohen, J.D.: An integrative theory of prefrontal cortex function. Annual Review of Neuroscience **24**(1), 167–202 (2001)

[47] Menon, V., Uddin, L.Q.: Saliency, switching, attention and control: A network model of insula function. Brain Structure and Function **214**(5–6), 655–667 (2010)

[48] Gao, W., Zhu, H., Giovanello, K.S., Smith, J.K., Shen, D., Gilmore, J.H., Lin, W.: Evidence on the emergence of the brain's default network from 2-week-old to 2-year-old healthy pediatric subjects. Proceedings of the National Academy of Sciences **106**(16), 6790–6795 (2009)

[49] Supekar, K., Musen, M., Menon, V.: Development of large-scale functional brain networks in children. PLoS Biology **7**(7), 1000157 (2009)

[50] Hennessey, B.A., Amabile, T.M.: Creativity. Annual Review of Psychology **61**, 569–598 (2010)

[51] Sawyer, R.K.: Explaining Creativity: The Science of Human Innovation. Oxford University Press, ??? (2012).

https://doi.org/10.1093/acprof:oso/9780199737574.001.0001

[52] Bradley, R.H., Caldwell, B.M.: The relation of infants' home environments to achievement test performance in first grade: A follow-up study. Child Development **55**(3), 803–809 (1984)

[53] Caldwell, B.M., Bradley, R.H.: HOME Inventory Administration Manual. (2003). https://www.ualr.edu/home/

[54] Bradley, R.H., Caldwell, B.M., Rock, S.L., Ramey, C.T., Barnard, K.E., Gray, C., Johnson, D.L.: Home environment and cognitive development in the first 3 years of life: A collaborative study involving six sites and three ethnic groups in north america. Developmental Psychology **25**(2), 217–235 (1989)

[55] Totsika, V., Sylva, K.: The home observation for measurement of the environment revisited. Child and Adolescent Mental Health **9**(1), 25–35 (2004)

[56] Wachs, T.D.: Necessary But Not Sufficient: The Respective Roles of Single and Multiple Influences on Individual Development. American Psychological Association, ??? (2000). https://doi.org/10.1037/10344-000

[57] Evans, G.W., Rosenbaum, J.: Self-regulation and the income-achievement gap. Early Childhood Research Quarterly **23**(4), 504–514 (2008)

[58] Rowe, M.L., Goldin-Meadow, S.: Differences in early gesture explain ses disparities in child vocabulary size at school entry. Science **323**(5916), 951–953 (2009)

[59] Landry, S.H., Smith, K.E., Swank, P.R.: Responsive parenting: Establishing early foundations for social, communication, and independent problem-solving skills. Developmental Psychology **42**(4), 627–642 (2006)

[60] Tamis-LeMonda, C.S., Bornstein, M.H., Baumwell, L.: Maternal responsiveness and children's achievement of language milestones. Child Development **72**(3), 748–767 (2001)

[61] Hart, B., Risley, T.R.: Meaningful Differences in the Lives of American Children. Paul H. Brookes Publishing, ??? (1995). https://products.brookespublishing.com/Meaningful-Differences-in-the-Lives-of-American-Children-P14.aspx

[62] Hirsh-Pasek, K., Adamson, L.B., Bakeman, R., Owen, M.T., Golinkoff,

R.M., Pace, A., Suma, K.: The contribution of early communication quality to low-income children's language success. Psychological Science **26**(7), 1071–1083 (2015)

[63] Yoshikawa, H., Aber, J.L., Beardslee, W.R.: The effects of poverty on the mental, emotional, and behavioral health of children and youth: Implications for prevention. American Psychologist **67**(4), 272–284 (2012)

[64] Duncan, G.J., Magnuson, K., Votruba-Drzal, E.: Moving beyond correlations in assessing the consequences of poverty. Annual Review of Psychology **68**, 413–434 (2017)

[65] Gilmore, J.H., Knickmeyer, R.C., Gao, W.: Imaging structural and functional brain development in early childhood. Nature Reviews Neuroscience **19**(3), 123–137 (2018)

[66] Knickmeyer, R.C., Gouttard, S., Kang, C., Evans, D., Wilber, K., Smith, J.K., Gilmore, J.H.: A structural mri study of human brain development from birth to 2 years. Journal of Neuroscience **28**(47), 12176–12182 (2008)

[67] Lenroot, R.K., Giedd, J.N.: Brain development in children and adolescents: Insights from anatomical magnetic resonance imaging. Neuroscience & Biobehavioral Reviews **30**(6), 718–729 (2006)

[68] Power, J.D., Fair, D.A., Schlaggar, B.L., Petersen, S.E.: The development of human functional brain networks. Neuron **67**(5), 735–748 (2010)

[69] Dosenbach, N.U., Nardos, B., Cohen, A.L., Fair, D.A., Power, J.D., Church, J.A., *et al.*: Prediction of individual brain maturity using fmri. Science **329**(5997), 1358–1361 (2010)

[70] Lebel, C., Beaulieu, C.: Longitudinal development of human brain wiring continues from childhood into adulthood. Journal of Neuroscience **31**(30), 10937–10947 (2011)

[71] Fields, R.D.: White matter in learning, cognition and psychiatric disorders. Trends in Neurosciences **31**(7), 361–370 (2008)

[72] Hanson, J.L., Chandra, A., Wolfe, B.L., Pollak, S.D.: Association between income and the hippocampus. PLoS One **6**(5), 18712 (2011)

[73] Luby, J., Belden, A., Botteron, K., Marrus, N., Harms, M.P., Babb, C., Barch, D.: The effects of poverty on childhood brain development: The mediating effect of caregiving and stressful life events. JAMA Pediatrics

167(12), 1135–1142 (2013)

[74] Hair, N.L., Hanson, J.L., Wolfe, B.L., Pollak, S.D.: Association of child poverty, brain development, and academic achievement. JAMA Pediatrics **169**(9), 822–829 (2015)

[75] Piccolo, L.R., Merz, E.C., He, X., Sowell, E.R., Noble, K.G., Pediatric Imaging, Neurocognition, and Genetics Study: Age-related differences in cortical thickness vary by socioeconomic status. PLoS ONE **11**(9), 0162511 (2016). https://doi.org/10.1371/journal.pone.0162511

[76] Gao, W., Alcauter, S., Elton, A., Hernandez-Castillo, C.R., Smith, J.K., Ramirez, J., Lin, W.: Functional network development during the first year: Relative sequence and socioeconomic correlations. Cerebral Cortex **25**(9), 2919–2928 (2015)

[77] Reynolds, A.J., Temple, J.A., Robertson, D.L., Mann, E.A.: Long-term effects of an early childhood intervention on educational achievement and juvenile arrest: A 15-year follow-up of low-income children in public schools. JAMA **285**(18), 2339–2346 (2001)

[78] Barnett, W.S.: Effectiveness of early educational intervention. Science **333**(6045), 975–978 (2011)

[79] Ramey, C.T., Campbell, F.A.: Preventive education for high-risk children: Cognitive consequences of the carolina abecedarian project. American Journal of Mental Deficiency **88**(5), 515–523 (1984)

[80] Campbell, F.A., Ramey, C.T., Pungello, E., Sparling, J., Miller-Johnson, S.: Early childhood education: Young adult outcomes from the abecedarian project. Applied Developmental Science **6**(1), 42–57 (2002)

[81] Muennig, P., Schweinhart, L., Montie, J., Neidell, M.: Effects of a prekindergarten educational intervention on adult health: 37-year follow-up results of a randomized controlled trial. American Journal of Public Health **99**(8), 1431–1437 (2009)

[82] Reynolds, A.J., Temple, J.A., White, B.A., Ou, S.R., Robertson, D.L.: Age 26 cost-benefit analysis of the child-parent center early education program. Child Development **82**(1), 379–404 (2011)

[83] Ramey, C.T., Ramey, S.L.: Early intervention and early experience. American Psychologist **53**(2), 109–120 (1998)

[84] Lewis, M.D.: The promise of dynamic systems approaches for an integrated account of human development. Child Development **71**(1), 36–43 (2000)

[85] Jung, R.E., Mead, B.S., Carrasco, J., Flores, R.A.: The structure of creative cognition in the human brain. Frontiers in Human Neuroscience **7**, 330 (2013)

[86] Beaty, R.E., Benedek, M., Barry Kaufman, S., Silvia, P.J.: Default and executive network coupling supports creative idea production. Scientific Reports **5**(1), 10964 (2015)

[87] Zelazo, P.D., Carter, A., Reznick, J.S., Frye, D.: Early development of executive function: A problem-solving framework. Review of General Psychology **1**(2), 198–226 (1997)

[88] Klingberg, T.: Development of a superior frontal-intraparietal network for visuo-spatial working memory. Neuropsychologia **44**(11), 2171–2177 (2006)

[89] Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A., Wager, T.D.: The unity and diversity of executive functions and their contributions to complex "frontal lobe" tasks. Cognitive Psychology **41**(1), 49–100 (2000)

[90] Kosslyn, S.M., Ganis, G., Thompson, W.L.: Neural foundations of imagery. Nature Reviews Neuroscience **2**(9), 635–642 (2001). https://doi.org/10.1038/35090055

[91] Johnson, M.H.: Interactive specialization: A domain-general framework for human functional brain development? Developmental Cognitive Neuroscience **1**(1), 7–21 (2011). https://doi.org/10.1016/j.dcn.2010.07.003

[92] Karmiloff-Smith, A.: Nativism versus neuroconstructivism: Rethinking the study of developmental disorders. Developmental Psychology **45**(1), 56–63 (2009). https://doi.org/10.1037/a0014506

[93] Bullmore, E., Sporns, O.: Complex brain networks: Graph theoretical analysis of structural and functional systems. Nature Reviews Neuroscience **10**(3), 186–198 (2009). https://doi.org/10.1038/nrn2575

[94] Bassett, D.S., Bullmore, E.T.: Small-world brain networks revisited. The Neuroscientist **23**(5), 499–516 (2017). https://doi.org/10.1177/1073858416667720

[95] Shonkoff, J.P., Levitt, P.: Neuroscience and the future of early childhood policy: Moving from why to what and how. Neuron **67**(5), 689–691 (2010). https://doi.org/10.1016/j.neuron.2010.08.032

[96] Fox, S.E., Levitt, P., Nelson III, C.A.: How the timing and quality of

early experiences influence the development of brain architecture. Child Development **81**(1), 28–40 (2010). https://doi.org/10.1111/j.1467-8624.2009.01380.x

[97] DiPrete, T.A., Eirich, G.M.: Cumulative advantage as a mechanism for inequality: A review of theoretical and empirical developments. Annual Review of Sociology **32**, 271–297 (2006). https://doi.org/10.1146/annurev.soc.32.061604.123127

[98] Dede, C.: Comparing frameworks for 21st century skills. In: Bellanca, J., Brandt, R. (eds.) 21st Century Skills: Rethinking How Students Learn, pp. 51–76. Solution Tree Press, ??? (2010). https://www.solutiontree.com/products/21st-century-skills

[99] Trilling, B., Fadel, C.: 21st Century Skills: Learning for Life in Our Times. Jossey-Bass, ??? (2009). https://www.wiley.com/en-us/9780470475386

[100] Kelley, T., Kelley, D.: Creative Confidence: Unleashing the Creative Potential Within Us All. Crown Business, ??? (2013). https://www.penguinrandomhouse.com/books/312696/creative-confidence-by-tom-kelley-and-david-kelley/

[101] Henriksen, D., Richardson, C., Mehta, R.: Design thinking: A creative approach to educational problems of practice. Thinking Skills and Creativity **26**, 140–153 (2017). https://doi.org/10.1016/j.tsc.2017.10.001