**Enhancing the Assessment of Spatial Reasoning Abilities: Integrating Problem-Solving Strategies with Multimodal Data and Machine Learning Approaches**

**Abstract**

This dissertation aims to comprehensive spatial ability assessment by integrating Multimodal Joint-Hierarchical Cognitive Diagnosis Modeling (MJ-DINA) with machine learning-based Graphical Network Analysis (GNA). Spatial ability is crucial in STEM education, significantly influencing problem-solving and comprehension. Traditional assessment methods often lack the granularity to diagnose specific cognitive strengths and weaknesses. By leveraging MJ-DINA, which incorporates multimodal data such as response accuracy, response time, and eye tracking data, alongside machine learning-based GNA, this research seeks to develop a comprehensive framework that provides detailed insights into individual spatial competencies, thereby informing personalized educational interventions.

**Introduction**

Spatial ability, the capacity to visualize, manipulate, and reason about spatial relationships, is fundamental in disciplines such as mathematics, engineering, and architecture. It significantly influences problem-solving and comprehension within these fields. Traditional assessment methods often lack the granularity to diagnose specific cognitive strengths and weaknesses, particularly neglecting the effect of problem-solving strategies.

Recent advancements in cognitive diagnosis models (CDMs) and machine learning offer promising avenues to address these limitations. CDMs provide a nuanced approach by evaluating specific cognitive attributes, enabling a deeper understanding of individual problem-solving strategies. Integrating machine learning techniques and Graphical Network Analysis (GNA), this research can model complex explore the relationships within response data and processing data, enhancing the precision and adaptability of these evaluations and offering additional information of problem-solving strategy.

This comprehensive approach allows for a detailed analysis of the cognitive processes underlying spatial problem-solving. By examining how individuals employ various strategies, such as mental rotation or mechanical reasoning, we can gain insights into their spatial reasoning skills. This, in turn, can inform personalized educational interventions, enhancing learning outcomes in STEM education.

**Research Objectives:**

This dissertation comprises three interrelated studies, each contributing to the overarching goal of enhancing spatial ability assessment through innovative methodologies:

**1.Estimating a Comprehensive General Spatial Ability Using Cognitive Diagnosis Models**

*Objective:* Develop and validate an assessment tool that evaluates various dimensions of spatial ability, including mental rotation, spatial visualization, and spatial orientation, utilizing Cognitive Diagnosis Models (CDMs) to provide detailed diagnostic information on individual cognitive strengths and weaknesses.

**2.Enhancing Spatial Ability Assessment: Integrating Problem-Solving Strategies in Object Assembly Tasks Using Multimodal Joint-Hierarchical Cognitive Diagnosis Modeling**

*Objective:* Investigate the incorporation of problem-solving strategies within object assembly tasks by employing Multimodal Joint-Hierarchical Cognitive Diagnosis Modeling (MJ-HCDM) to capture and analyze multimodal data, such as response accuracy, response time, and visual fixation patterns, offering a comprehensive understanding of cognitive processes involved in spatial reasoning.

**3.** **Analyzing Cognitive Strategies through Machine Learning and Eye-Tracking Metrics**

*Objective:* Leverage Machine Learning approach to classify cognitive strategies by exploring five major eye-tracking metrics: proportional time on matrix (PTM), latency to first toggle (LFT), rate of latency to first toggle (RLT), number of toggles (NOT), and rate of toggling (ROT).

analyzing the complex relationships and patterns in spatial reasoning problem-solving, aiming to enhance predictive accuracy and adaptability of spatial ability assessments, and to uncover insights into the underlying cognitive structures.

**Methodology**

This dissertation employs a comprehensive methodology to assess spatial abilities and problem-solving strategies, integrating advanced cognitive diagnostic models and machine learning techniques. The approach is structured as follows:

Test Development:

Design Assessment Items: Develop a battery of tasks targeting various facets of spatial ability, including mental rotation, spatial visualization, and spatial orientation. Ensure content validity through reviews by subject matter experts, refining items to accurately measure the intended constructs.

Data Collection:

Administer the assessment to a diverse cohort of young children to capture a wide range of developmental stages. Simultaneously collect cognitive processing data, such as response accuracy, response time, and visual fixation counts, during object assembly tasks to gain insights into problem-solving strategies.

Application of Cognitive Diagnosis Models (CDMs):

Employ Higher-Order Latent Class Modeling (H-LLM) to analyze item validity and reliability, examine response patterns, and diagnose specific cognitive attributes, providing a nuanced understanding of individual spatial abilities. Implement models that integrate multiple data sources (e.g., response time, fixation counts) to enhance diagnostic precision in assessing problem-solving strategies.

Machine Learning Integration:

Utilize machine learning-based GNA to analyze spatial reasoning problem-solving, identifying patterns and relationships that inform the assessment framework.

Validation:

To ensure the robustness and efficacy of the proposed assessment framework, a comprehensive validation process will be conducted.

Models for Comparison:

Multimodal Joint-Hierarchical Cognitive Diagnosis Model (MJ-HCDM): Integrates multiple data sources to provide a nuanced understanding of cognitive attributes.

Machine Learning-Based Graphical Network Analysis (ML-GNA): Utilizes machine learning algorithms to model complex relationships within spatial reasoning tasks.

Traditional Cognitive Diagnosis Models (CDMs): Such as the Generalized DINA (G-DINA) model, which analyzes response patterns to diagnose cognitive strengths and weaknesses.

Item Response Theory (IRT) Models: Traditional models that estimate latent traits based on item responses.

**Evaluation Metrics:**

Model Fit Indices: Assess how well each model fits the observed data using indices such as Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC).

Classification Accuracy: Evaluate the precision with which each model classifies individuals' mastery of specific cognitive attributes.

Predictive Validity: Examine the extent to which each model accurately predicts performance on related tasks or future assessments.

**Reliability Measures:**

Determine the consistency of the assessment outcomes across different samples and contexts.

**Statistical Analyses**

Goodness-of-Fit Tests: Perform tests to compare the observed data with the expected outcomes under each model, identifying the model that best represents the data.

Cross-Validation: Implement cross-validation techniques to assess the generalizability of the models to independent datasets.

**Benchmarking Against Established Models**

**Traditional CDMs and IRT Models: Serve as benchmarks to evaluate the added value of MJ-HCDM and ML-GNA in capturing complex cognitive processes and providing detailed diagnostic information.**

**Interpretation of Results**

Diagnostic Information: Analyze the depth and specificity of the diagnostic information provided by each model, particularly in identifying individual problem-solving strategies and spatial reasoning skills.

**Practical Implications: Consider the feasibility of implementing each model in educational settings, including the complexity of data requirements and computational resources.**

**This validation process aims to establish the reliability, validity, and practical utility of the proposed assessment framework, ensuring its effectiveness in accurately diagnosing spatial abilities and informing personalized educational interventions.**

**Expected Contributions:**

* **Theoretical Advancement:** Provide a novel framework that integrates CDMs with machine learning for spatial ability assessment.
* **Practical Application:** Develop an assessment tool that educators can use to diagnose and support the development of students' spatial abilities.
* **Research Implications:** Offer insights into the cognitive processes underlying spatial ability, informing future educational research and practice.

**Literature Review:**

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