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Probabilistic Information and Network Evaluation System (PINES): A Bayesian Framework for Advancing Psychometric Testing

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As educational and cognitive assessments advance, there is a growing need for innovative, evidence based methodologies that offer deeper insights into students'abilities, knowledge representation, and response reliability. Contemporary assessment systems face the challenge of capturing nuanced insights into student learning while ensuring measurement validity, going beyond traditional scoring, offering valuable perspectives on students'cognitive processes, knowledge structures, and response patterns while detecting potential validity threats such as rapid guessing or cheating behavior. We propose the Probabilistic Information and Network Evaluation System (PINES), a novel framework that integrates Bayesian networks (BNs) and information theory to enhance psychometric scoring and reliability assessment. PINES incorporates item interdependencies and provides deeper insights into the cognitive processes underlying these dependencies. The framework begins by constructing a Directed Acyclic Graph (DAG) to model item relationships, from which conditional probabilities for each item are calculated based on responses to related items. This approach ensures that the scoring system accurately captures the interconnected nature of test items. PINES employs self-information to measure the "surprise"or unexpectedness of each response, given its expected probability derived from the DAG. This allows to generate a weighted score that reflects the informativeness of each response, allowing also the framework to identify potentially anomalous or unreliable responses. By computing confidence intervals, PINES enhances the interpretability and robustness of the results. Furthermore, the framework employs entropy-based metrics to evaluate the uncertainty in response distributions. For each item, PINES measures how a respondent's answers deviate from the sample average entropy, enabling the detection of specific cognitive patterns or difficulties in their responses. This granular analysis provides deeper insights into individual response strategies and potential inconsistencies. To assess overall reliability, PINES calculates a weighted reliability score for each respondent based on the number of incoherent and highly improbable responses. This score is normalized, with lower values indicating higher reliability, offering a clear and quantifiable measure of response consistency. To demonstrate its practical utility, we applied PINES to the Raven's Colored Progressive Matrices (CPM), using a Bayesian network developed in a prior study involving a sample of 40 first-year primary school children (mean age = 6.68 ± 0.36 years; 52.5% male). We selected three cases with identical total scores, two real respondents and one with random responses, to illustrate how PINES analyzes individual response patterns, detects improbable responses, and assesses reliability. Regarding the three cases PINES identified two highly improbable responses in the first case, yielding a high reliability score (0.172), while in the second with three incoherent responses received a medium reliability score (0.207). In the random response case, eight incoherent and five highly improbable responses were flagged, resulting in a low reliability score (0.534). In conclusion, PINES represents a novel perspective in psychometric methodologies. By explicitly modeling item dependencies and leveraging information theory, it provides a more accurate -at the individual level - and detailed assessment of response reliability. Furthermore, PINES is adaptable to a wide range of psychometric tests and contexts, making it a versatile tool for cognitive testing and beyond.

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