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Towards Adaptive Learning: A Bayesian Knowledge Tracing Approach to Student Skill Prediction Bayesian Knowledge Tracing for Modeling Daily Living Skills in Children with ASD

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Abstract: Autism Spectrum Disorder (ASD) presents challenges in mastering Activities of Daily Living (ADLs), which are essential for independence. This study applies Bayesian Knowledge Tracing (BKT) to model the mastery of five ADL skills—eating, dressing, toothbrushing, combing, and bathing—using data from 27 learners (1,350 responses). BKT parameters, including initial mastery, learning transition, guessing, and slipping, were used to estimate individual learning trajectories. Results showed that eating was the easiest skill (predicted mastery = 0.78), while bathing and combing were the most difficult (<0.55). The model achieved an overall accuracy of 0.62, with strong detection of actual mastery (TP = 722) but a high false-positive rate (FP = 429), indicating sensitivity to the guessing parameter. Learning curves and heatmaps revealed substantial inter-student variability. A comparative evaluation with the Performance Factors Analysis (PFA) model showed that BKT achieved higher overall predictive accuracy (BKT = 0.6356; PFA = 0.5917), while PFA demonstrated a higher AUC (0.6747) but exhibited strong positive-class bias in classification. These findings demonstrate the usefulness of BKT in modeling ADL development and highlight its potential for adaptive learning systems that support personalized interventions for ASD learners.

Keywords: Autism Spectrum Disorder, Activities of Daily Living, Bayesian Knowledge Tracing, Adaptive Learning

INTRODUCTION

Autism Spectrum Disorder (ASD) is a complex neurodevelopmental condition characterized by challenges in social communication, restricted interests, and repetitive behaviors. The prevalence of ASD has notably risen, with recent estimates indicating that approximately 1 in 44 children in the United States are diagnosed with this condition (Ahmed et al., 2021). This trend underscores the urgent need for effective interventions aimed at enhancing the daily functioning and independence of children with ASD. A critical area of focus for these children is the mastery of Activities of Daily Living (ADLs), which encompass fundamental skills such as eating, bathing, dressing, brushing teeth, and grooming. Proficiency in ADLs is essential, as it fosters autonomy and lays the groundwork for social integration, academic success, and overall quality of life (Forbes et al., 2021).

Nonetheless, many children with ASD face significant delays in acquiring these necessary ADLs. Traditional instructional methods often rely on therapist-led interventions that require high levels of resource commitment, including the continuous involvement of therapists, teachers, and caregivers. These methods tend to yield slow progress and often lack mechanisms to systematically track or model how children acquire skills over time. Additionally, conventional approaches do not incorporate data-driven analysis that can reveal individual learning trajectories, thereby highlighting the need for more systematic and scalable tools to support the development of ADLs (Kanhirakadavath & Chandran, 2022) (Barua et al., 2022).

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Recent advancements in Artificial Intelligence (AI) and Educational Data Mining (EDM) have opened promising pathways for personalized learning support in this context(Herianingtyas et al., 2023)(Choi et al., 2023)(Chanthiran et al., 2022). One noteworthy approach is Bayesian Knowledge Tracing (BKT), a probabilistic framework that models student learning by estimating knowledge states based on performance data. BKT dynamically updates predictions of skill mastery as learners engage with tasks, making it a potential tool for tracking ADL acquisition in real time. By applying BKT to ADLs, it becomes possible to obtain a clearer representation of how mastery evolves, offering insights into learning progression that can complement traditional teaching methods (Barua et al., 2022).

The present study aims to leverage BKT to model the learning trajectories of students across five essential daily activities, treating these as discrete skills to be evaluated. Data collected from 27 learners, each engaging in ten tasks per skill, will be analyzed to assess the predictive capacity of BKT from multiple perspectives, such as overall prediction accuracy, confusion matrix analysis for classification reliability, and visualization of learning trends. This multifaceted evaluation not only seeks to identify the strengths and limitations of BKT in this new context but also highlights its significant implications for understanding skill mastery in inclusive educational settings for children with ASD(Gentil-Gutiérrez et al., 2022).

Addressing a critical research gap, this study focuses on applying BKT to non-academic, functional skills like ADLs, which have seen limited exploration in previous literature. It expands the existing body of research by integrating performance evaluation with pedagogical interpretation, thereby extending the scope of BKT studies into areas pertinent to inclusive education for children with special needs. This integration of AI and data-driven modeling strategies could unlock new potential for enhancing the educational experiences and outcomes of children with ASD (Donoso et al., 2023).

In conclusion, as the prevalence of ASD continues to rise, the need for innovative approaches to support the acquisition of ADLs becomes increasingly urgent. By adapting BKT for this purpose, the current research aims to contribute valuable insights that can inform the design of effective, personalized interventions that not only facilitate daily living skills but also promote long-term independence and quality of life for children on the autism spectrum.

In conclusion, as the prevalence of ASD continues to rise, the need for innovative and systematic approaches to support the acquisition of ADLs becomes increasingly urgent. By applying BKT for this purpose, the current research aims to contribute valuable insights that can inform the development of effective interventions that facilitate daily living skills and promote long-term independence and quality of life for children on the autism spectrum.

LITERATURE REVIEW

Research on the development of AI-based learning systems for children with Autism Spectrum Disorder (ASD) has advanced significantly in recent years. Various approaches have been explored, including machine learning and rule-based systems, to support the acquisition of Activities of Daily Living (ADLs). However, most existing studies still rely on deterministic or rule-based methods, which are less capable of capturing the dynamic and individualized developmental trajectories of children with ASD (Ghosh et al., 2021).

The Bayesian Knowledge Tracing (BKT) approach employed in this study offers an innovative solution by enabling the personalization of task difficulty levels according to each child's developmental progress (Minn et al., 2022)(Liu et al., 2021)(Minn, 2020). Unlike prior research that often applied fixed models, BKT allows the system to dynamically adjust learning challenges based on the probabilistic estimation of skill mastery, which is continuously updated as the child interacts with the system (Hozella et al., 2021)(Badrinath et al., 2021). Another strength of this model lies in its ability to trace individual developmental progress by incorporating historical performance data, enabling the generation of more accurate insights into each child's learning trajectory.

In addition to BKT, several alternative knowledge-tracing models have been introduced in the literature, one of the most prominent being Performance Factors Analysis (PFA). PFA is a logistic regression–based approach that predicts student performance by considering both prior successes and failures as weighted predictors of learning (Pavlik et al., 2009). Unlike BKT, which relies on hidden states and probabilistic transitions, PFA models learning as a direct function of observable behavior, making it more flexible for datasets with sparse or irregular learning sequences. Studies comparing PFA and BKT have shown that PFA often performs competitively, particularly in tasks where repeated practice strongly influences learning outcomes (Gong et al., 2011). However, BKT remains advantageous when modeling latent knowledge states or when understanding the learning process itself is a primary objective.

In contrast to studies that continue to rely on heuristic strategies or conventional machine learning techniques, the use of BKT—and its comparison to PFA in this research—supports more precise and individualized monitoring of skill development. This study contributes novelty by extending the application of knowledge-tracing models to functional, non-academic skills such as ADLs, an area that remains underexplored, and by providing a probabilistic and comparative framework to better understand how children with ASD acquire essential daily living skills.

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METHOD

In This study employs a systematic methodology to design and evaluate an AI-based model for supporting Activities of Daily Living (ADLs) in children with Autism Spectrum Disorder (ASD) using the Bayesian Knowledge Tracing (BKT) approach. The overall research process is depicted in Figure 1.

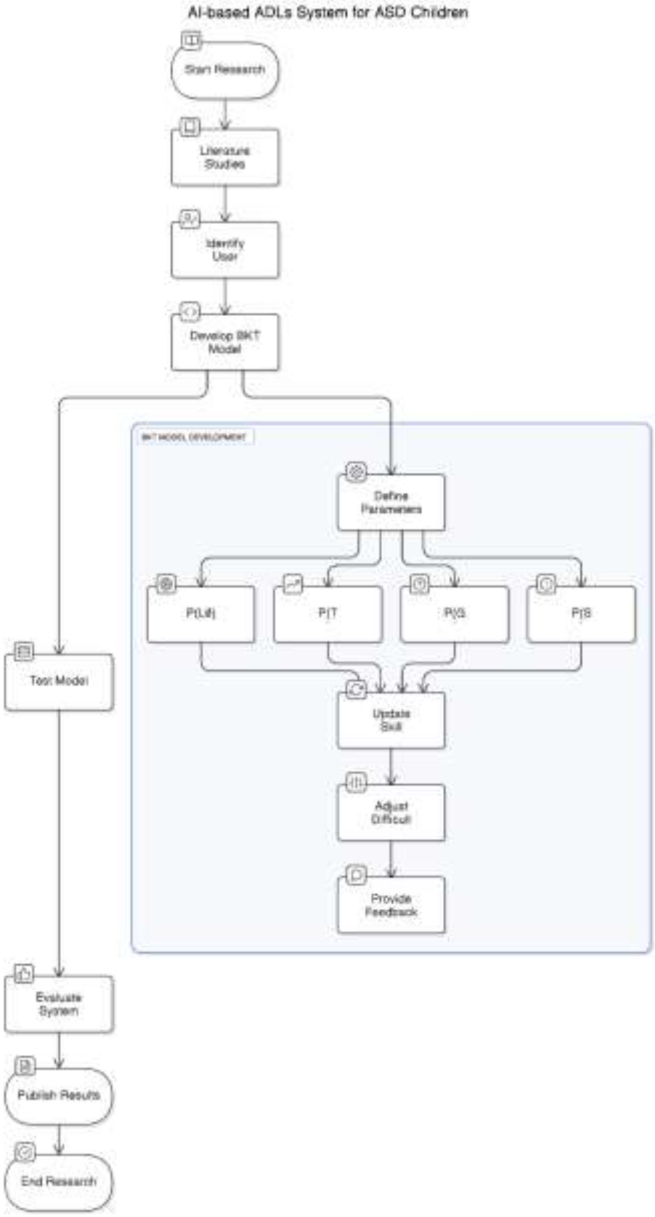

Fig. 1 AI-Based ADLs System for ASD Children Using the BKT Approach

The process began with a preliminary study in which a literature review was conducted to explore the challenges faced by children with ASD in mastering ADLs and to identify the limitations of existing instructional methods. At this stage, the target users were defined, and the rationale for employing BKT was established.

Following this, the BKT model was developed by defining its key parameters, namely the probability of prior knowledge (P(Lθ)), the probability of learning (P(T)), the probability of guessing correctly without mastery (P(G)), and the probability of slipping despite mastery (P(S)). These probabilistic components form the foundation of the model and allow it to represent the dynamic process of skill acquisition in a structured manner. The Bayesian Knowledge Tracing (BKT) model represents student knowledge as a hidden binary variable indicating whether a skill has been mastered. The model uses four core parameters:

- P(Lθ): initial probability of mastery
- P(T): learning probability (transition from unmastered → mastered)

*name of corresponding author

- P(G): guessing probability
- P(S): slipping probability

The belief update follows standard BKT equations:

- Posterior after observing a correct response:

$$P(L_t\,|correct) = \frac{P(L_t)(1-P(S))}{P(L_t)(1-P(S))+(1-P(L_t))P(G)} \quad (1)$$

- Posterior after observing an incorrect response:

$$P(L_t\,|incorrect) = \frac{P(L_t)P(S)}{P(L_t)P(S)+(1-P(L_t))(1-P(G))} \quad (2)$$

- Learning transition:

$$P(L_{t+1}) = \; P(L_t|obs) + \big(1 - P(L_t|obs)\big)P(T) \quad (3)$$

A full implementation was developed using the pyBKT library, with custom preprocessing, student-skill mapping, and post-hoc prediction extraction.

Once the model parameters were defined, the adaptive learning process was implemented. In this process, every learner's interaction with ADL-related tasks was treated as input to the BKT framework. Each correct or incorrect response updated the learner's estimated mastery probability, which in turn determined the level of difficulty for subsequent tasks. This adaptive mechanism ensured that learning materials were continuously aligned with the learner's evolving abilities, neither overwhelming the learner with overly difficult tasks nor under-stimulating them with tasks that were too easy.

To support the learning experience, the system was also designed to provide immediate feedback after each task. Feedback was tailored to the learner's current skill state and aimed to reinforce correct behaviors while offering guidance when errors occurred. This approach not only improved engagement but also encouraged gradual mastery of ADLs in a supportive manner.

The developed model was then evaluated from multiple perspectives. Prediction accuracy was measured to determine how closely the model's estimates of skill mastery aligned with actual performance. A confusion matrix was constructed to assess the reliability of classification, distinguishing between true and false predictions of mastery. In addition, learning trends were visualized to reveal the progression of skill acquisition across different ADLs. Together, these analyses provided a comprehensive view of the model's predictive performance and its potential in supporting adaptive learning.

Finally, the outcomes of the model development and evaluation were documented and disseminated through academic reporting and publication. This ensured that the findings not only contributed to the advancement of AI-based adaptive learning technologies but also provided insights into the pedagogical applications of BKT in supporting children with ASD to acquire essential daily living skills.

Comparative Modeling Approach (BKT vs. PFA)

To strengthen the robustness and generalizability of the evaluation, a comparative experiment was conducted using the Performance Factors Analysis (PFA) model, a logistic regression–based framework widely applied in learning analytics to estimate student performance through cumulative practice features. Incorporating PFA as a baseline comparison enables the study to benchmark Bayesian Knowledge Tracing (BKT) against a non-Bayesian, feature-driven approach that does not rely on latent state modeling. This comparison is essential because PFA represents a contrasting paradigm—one that models performance based on observable practice counts (e.g., prior successes and failures), whereas BKT models learning as a hidden knowledge state updated probabilistically over time. By evaluating both models on the same learning dataset and using aligned performance metrics, the study ensures a fair assessment of predictive capability, model behavior, and suitability for adaptive ADLs learning contexts. The inclusion of this comparative analysis not only responds to the need for broader methodological validation but also highlights the unique advantages and limitations of each model within ASD-focused learning environments.

RESULT

In the results of this study, data were collected from 27 students who completed a total of 50 questions across five main daily activities: dressing, brushing teeth, eating, bathing, and combing hair. Each activity consisted of 10 questions, yielding 1,350 responses in total. These responses provided a comprehensive representation of students' mastery levels across the targeted activities. The dataset was subsequently analyzed using the Bayesian Knowledge Tracing (BKT) model to estimate the probability of skill acquisition over time and to compare the actual responses with the model's predictions.

Analysis Results

The analysis was conducted using the Bayesian Knowledge Tracing (BKT) model, which estimates the likelihood that a student has mastered a particular skill based on their interactions with the system. The model incorporates four key parameters: the initial probability of skill mastery (P(L0)), the probability of acquiring the skill after practice (P(T)), the probability of producing a correct response despite not having mastered the skill (P(G)), and the probability of producing an incorrect response despite having mastered the skill (P(S)) (Minn, 2020)(Rizvi et al., 2022). The findings reveal that the BKT model provides representative estimations of students' learning patterns, as evidenced by the consistency between predicted mastery levels and actual performance. Notably, the presence of guessing (P(G)) and slipping (P(S)) underscores the complexity of accurately modeling student performance, as these parameters highlight situations where observed responses may not fully reflect true skill mastery. This reinforces the pedagogical value of BKT in adaptive learning, since the model does not solely rely on surface-level correctness but instead accounts for deeper probabilistic estimates of student understanding.

Learning Curve

The learning curve illustrates the progression of students' average accuracy in performing daily activities as the number of practice sessions increases. The analysis reveals marked differences across activities. Eating emerges as the highest and most stable skill, with accuracy approaching 0.78, suggesting that this activity is relatively easier to acquire and consistently mastered by students with ASD. In contrast, dressing and toothbrushing demonstrate positive but more moderate trends, with accuracy levels ranging between 0.62 and 0.66, reflecting the greater complexity of skills that require fine motor coordination and sequential actions. Combing occupies an intermediate position with an accuracy of around 0.52, but its variability across students highlights notable individual differences in mastery. Bathing, on the other hand, presents the lowest and most fluctuating curve, remaining below 0.55, which underscores its status as the most challenging activity to learn due to its multifaceted nature and reliance on a combination of fine and gross motor skills.

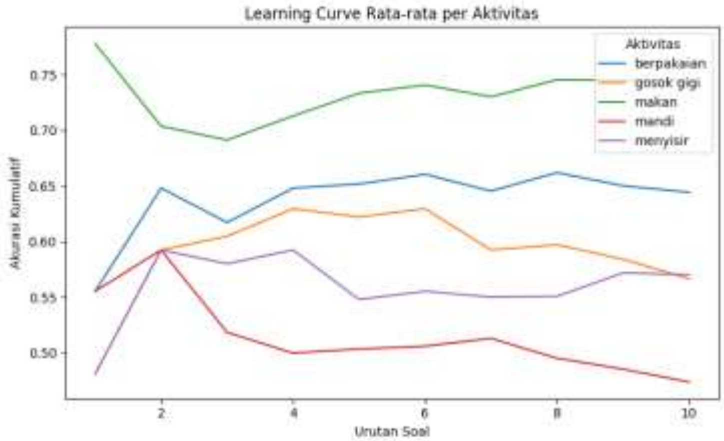

Figure 2. Average learning curve per activity

The learning curve demonstrates that ADLs have varying levels of difficulty, consistent with the literature stating that simpler motor skills are mastered faster than complex skills involving longer action sequences and fine motor control. These differences emphasize the urgency of using adaptive models such as BKT to adjust difficulty levels according to each child's needs.

Predicted Probability of Mastery per Activity

The probabilistic calculations of the BKT model for the five main activities revealed distinct levels of predicted skill mastery. Eating demonstrated the highest probability of mastery at 0.78, suggesting that this activity is relatively easier for students to learn and perform consistently. Dressing and toothbrushing followed with moderate probabilities of 0.68 and 0.62, respectively, reflecting their greater complexity due to the need for motor coordination and sequential actions. In contrast, combing showed a lower mastery probability of 0.52, indicating substantial variation among students, while bathing recorded the lowest probability at 0.48, confirming its status as the most challenging activity to master. These results underscore the heterogeneous nature of daily living skills and highlight the necessity of adaptive learning approaches that can personalize support based on the difficulty of each activity.

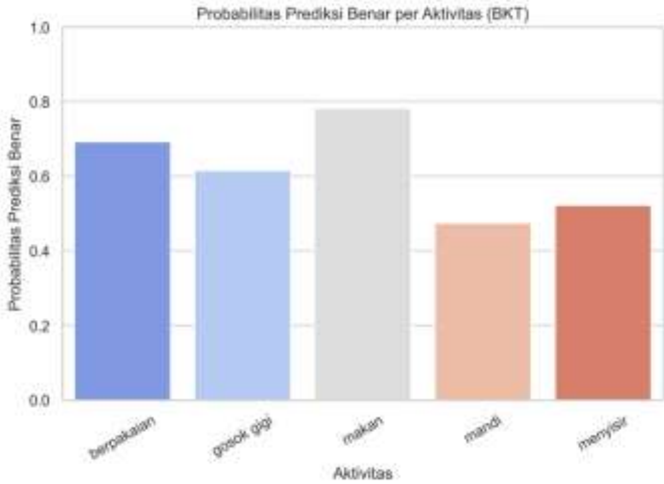

Figure 4. Predicted mastery probability per activity

These results are consistent with the theory of ADL development in ASD children, where skills performed more routinely every day (eating) tend to be mastered faster compared to activities less frequently performed without supervision (bathing). The low probabilities for bathing and combing highlight intervention areas that should be prioritized in adaptive learning design.

Distribution of Correct–Incorrect Responses

The analysis of response distribution further illustrates the varying levels of difficulty across activities. Eating and dressing were predominantly associated with correct responses, suggesting that these skills are relatively well established among students. Toothbrushing presented a more balanced distribution between correct and incorrect answers, indicating moderate complexity and variation in mastery. Bathing, however, was characterized by a greater proportion of incorrect responses, highlighting the challenges students face in performing this activity independently. Meanwhile, combing exhibited considerable variation across learners, reflecting differences in individual abilities and the nuanced demands of this skill. Collectively, these findings reinforce the notion that activities of daily living vary in difficulty and highlight the importance of adaptive interventions to address skill-specific challenges.

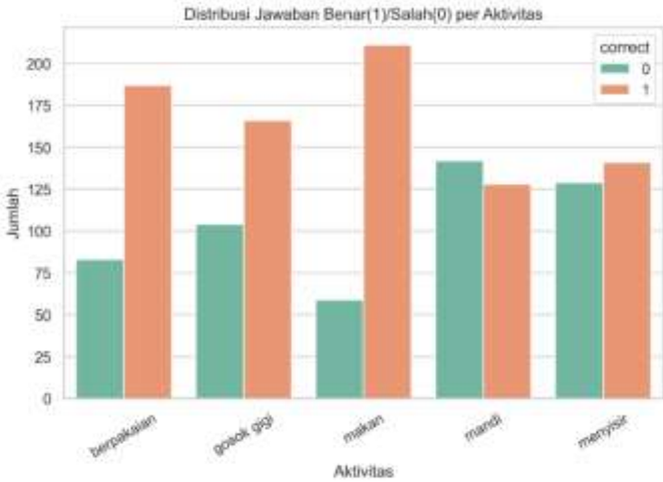

Figure 5. Response distribution

This distribution confirms that student performance varies not only between activities but also within the same skill context. Therefore, adaptive systems must consider the dynamics of performance changes, not just the final results.

Student–Activity Heatmap

The heatmap shows accuracy variations across students. Some students, such as S13, S19, and S26, demonstrate high performance in almost all activities. Conversely, students like S6, S21, and S23 experience

*name of corresponding author

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difficulties with complex activities (bathing, combing). Eating activities are relatively easier to master consistently across nearly all students.

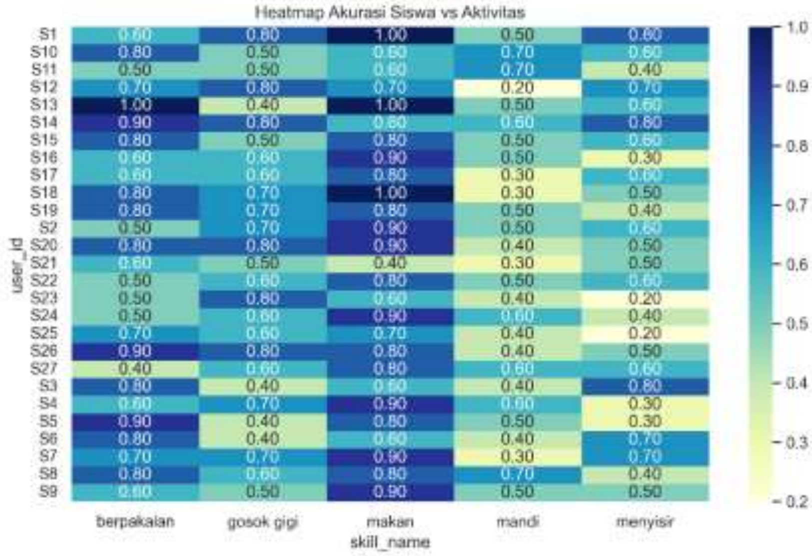

Figure 6. Heatmap of Student vs. Activity Accuracy

The differences among students indicate heterogeneity in abilities within the ASD population. These findings reinforce the relevance of using BKT, as the model can adjust predictions based on individual performance. Theoretically, this aligns with the principle of personalized learning in inclusive education.

Overall, the results demonstrate that the BKT model is effective in capturing learning dynamics of ADLs among ASD students, although certain parameters such as guessing contribute to prediction biases. These findings support the potential of BKT as a foundation for developing adaptive learning systems tailored to individual needs.

Model Comparison: Bayesian Knowledge Tracing vs. Performance Factors Analysis

To strengthen the evaluation of the proposed approach, a comparative experiment was conducted between Bayesian Knowledge Tracing (BKT) and Performance Factors Analysis (PFA), a logistic regression–based model widely utilized in knowledge tracing research. This comparison provides a benchmark to determine whether BKT offers advantages over a non-Bayesian, feature-based predictive model. The comparison uses the same dataset and performance metrics (accuracy, confusion matrix, precision, recall, and F1-score). The results are shown in Table 1.

Table 1. Model Performance Comparison (BKT vs. PFA)

Metric	BKT	PFA
Accuracy	0.6356	0.5917
AUC	–	0.6747
Precision (class 1)	0.65	0.59
Recall (class 1)	0.88	1.00
F1-Score (class 1)	0.75	0.74
True Positives	731	200
True Negatives	127	0
False Positives	390	138
False Negatives	102	0

The results indicate clear performance differences between the two approaches. BKT demonstrates higher overall accuracy (63.56%) compared with PFA (59.17%), suggesting that the probabilistic temporal modeling employed by BKT more effectively captures the sequential nature of ADL learning. Furthermore, BKT provides a more balanced classification capability, as reflected in its ability to correctly identify both mastery and non-mastery states. This is evident from the presence of 127 true negatives in BKT predictions, whereas PFA fails to identify any non-mastery cases, resulting in zero true negatives and a tendency to overpredict mastery.

Despite this limitation, PFA achieves perfect recall (1.00) for predicting the mastery class, meaning it successfully labels all actual mastery cases as positive. However, this comes with a substantial trade-off: PFA also generates a high number of false positives and completely misses the non-mastery classification. BKT, on the other hand, offers a more conservative and realistic estimation of mastery progression, with lower false positives and a stronger ability to differentiate between genuinely mastered and not-yet-mastered skills.

*name of corresponding author

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In terms of predictive discrimination, PFA attains an AUC value of 0.6747, indicating acceptable separability between classes, but this advantage does not translate into well-balanced classification outcomes. The F1-score is also slightly higher in BKT (0.75) compared to PFA (0.74), reinforcing BKT's overall stronger predictive reliability.

Overall, the comparative findings reveal that while PFA is capable of detecting general mastery trends, its strong bias toward predicting all responses as correct limits its usefulness for fine-grained adaptive learning applications. BKT remains the more suitable model for ADL skill prediction due to its balanced performance, interpretability, and ability to capture learner progression over time—key requirements for designing adaptive interventions for children with ASD.

DISCUSSIONS

This study investigated the application of Bayesian Knowledge Tracing (BKT) to model the mastery of Activities of Daily Living (ADLs) among children with Autism Spectrum Disorder (ASD). The findings confirm that ADLs vary considerably in difficulty: eating emerged as the skill with the highest mastery probability, while bathing and combing remained the most challenging. These patterns are consistent with developmental studies indicating that routine, low-complexity tasks are more readily acquired, whereas multi-step motor activities require longer learning trajectories. The learning curves and heatmap analysis further illustrated substantial heterogeneity across students, reinforcing the need for personalized learning models capable of adapting to individual profiles within the ASD population.

The confusion matrix provided deeper insight into the predictive behavior of the BKT model. A strong True Positive rate demonstrated BKT's effectiveness in detecting actual mastery, but the relatively high False Positive rate suggested a tendency to overestimate performance, influenced by the guessing parameter. This finding carries pedagogical implications: an adaptive system using BKT should avoid prematurely assuming mastery, as doing so may reduce necessary practice opportunities for more complex skills.

To strengthen the evaluation, a comparative analysis was performed using the Performance Factors Analysis (PFA) model. The results showed that BKT achieved higher predictive accuracy (0.6356) than PFA (0.5917). While PFA demonstrated higher recall, it failed to produce any true negatives, indicating an overgeneralization toward predicting mastery. This reinforces BKT's advantage in domains where distinguishing between mastered and unmastered states is essential. Unlike PFA, BKT's probabilistic framework allows it to incorporate temporal transitions and maintain interpretable latent-state updates, making it more suitable for modeling sequential learning processes in ADLs.

Overall, the findings validate BKT as a robust model for monitoring and predicting the development of daily living skills among ASD learners. Its ability to represent latent mastery states, update beliefs dynamically, and capture individual variability underscores its relevance for adaptive learning systems. Nonetheless, model limitations—such as sensitivity to parameter calibration and susceptibility to overestimation—indicate opportunities for future refinement. Integrating richer behavioral features, exploring hybrid models such as DKT or BKT-LSTM, and evaluating system performance in real intervention settings may further enhance predictive reliability and support the design of more effective, personalized ADL learning tools for children with ASD.

CONCLUSION

This study examined the use of Bayesian Knowledge Tracing (BKT) to model the mastery of Activities of Daily Living (ADLs) among children with Autism Spectrum Disorder (ASD). Using performance data across five daily activities, the model successfully captured variations in task difficulty and individual learning trajectories. Routine skills such as eating showed higher mastery probabilities, while more complex activities—including bathing and combing—remained challenging for many learners. These findings align with established developmental patterns in ADL acquisition and highlight the heterogeneity of skill mastery within the ASD population.

The evaluation demonstrated that BKT provides meaningful and interpretable estimates of learner mastery, with higher predictive accuracy than the comparative Performance Factors Analysis (PFA) model. However, the confusion matrix revealed that BKT may overestimate mastery in some cases, emphasizing the importance of careful parameter calibration and the need for broader contextual data to refine predictions.

Overall, the study affirms BKT as a viable method for modeling ADL skill development and a promising foundation for future adaptive learning systems. To strengthen its practical application, further research should incorporate larger datasets, additional behavioral features, and comparisons with more sophisticated models such as IRT-based approaches or deep knowledge tracing. Integrating the model into real-world intervention environments will also be essential for validating its utility in supporting personalized ADL learning for children with ASD.

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