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Mathematical modeling and intervention strategy analysis of social cognitive characteristics and interpersonal skills in children with autism

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Abstract. The increasing prevalence and number of autism (Autism Spectrum Disorder, ASD) cases worldwide in recent years have heightened awareness of the condition. Driven by concern for the well-being of children with autism and aiming to provide them with effective behavioral guidance and support, this study investigated and quantified the social cognitive characteristics and interpersonal skills of 73 autistic children. The relationship between cognitive characteristics and interpersonal skills was established using a deep learning neural network. Furthermore, multiple linear regression and grey relational analysis models were employed to explore the influence of various social cognitive characteristics on interpersonal skills. The results indicate that the cognitive representation process and behavioral motivation (attention process, cognitive representation process, behavior generation process, motivation process, motivation) in autistic children exhibit relatively stronger associations with interpersonal skills. The findings of this study provide a reference for developing targeted and effective intervention strategies for autistic children, helping them build fulfilling lives and realize their personal potential.

Keywords: Autism Spectrum Disorder, social cognitive characteristics, interpersonal skills, neural network, multiple linear regression, grey relational analysis

1. Introduction

Since the mid-20th century, the recorded number and prevalence of autism cases globally have shown a generally increasing trend year by year. Autism has become the leading cause of mental disability among children in China [1], yet its pathogenic causes remain unknown, and effective pharmacological treatments are lacking. Previous research has primarily focused on investigating the causes of autism and developing diagnostic methods, proposing etiological factors such as genetic influences and diagnostic schemes for different populations. However, research on autism treatment is relatively scarce, and studies specifically addressing how to provide services and guidance for autistic individuals are even rarer [2-4]. Therefore, to provide more scientifically sound assistance to autistic children through "treatment" targeting various aspects with different weights, this study takes the social cognitive characteristics of autistic children as its starting point and sets the improvement of interpersonal skills as the "treatment" goal. The rationale for this choice and the research process will be explained below.

2. Problem analysis

As a member of the Morning Star Club, an autism care club, we observed during volunteer activities that autistic children often exhibit social impairments. Deficits in social abilities are one of the primary symptoms of autism and a key factor in directly diagnosing Autism Spectrum Disorder [5]. Autism Spectrum Disorder is a syndrome primarily defined in behavioral terms (including social impairments, delayed language development, restricted interests, repetitive/stereotyped behaviors, and often below-average intelligence) but is generally associated with varying degrees of cognitive deficits. Understanding the cognitive processes in autism is a prerequisite for a comprehensive understanding of how this syndrome develops and is essential for designing effective strategies to ameliorate these cognitive deficits [6]. Consequently, we investigated and quantified the cognitive characteristics (including attention process, cognitive representation process, behavior generation process, motivation process, motivation) [7-10] and interpersonal skills (including response to calls, verbal expression, facial expressions and body language, social interaction, emotional expression and regulation, establishing and maintaining friendships) of 73 autistic children, and explored the associations between various cognitive characteristics and social skills [11]. By identifying the most influential cognitive characteristics, we aim to formulate strategies to improve cognitive deficits, thereby effectively enhancing the social skills of autistic children.

3. Basic assumptions

- The surveyed cognitive and social status of autistic children is relatively stable over a period of time. Autism is a neurodevelopmental disorder; its core symptoms are typically persistent and do not change significantly in the short term. The cognitive and social abilities of autistic children tend to be relatively stable.
- The surveyed autistic children exhibit significant characteristics primarily related to Autism Spectrum Disorder, with no other significant mental disabilities or minimal impact. Autism is generally considered a distinct diagnosis; its core symptoms are concentrated in social communication, behavioral patterns, etc., and are not accompanied by other severe mental illnesses. This assumption simplifies the characteristics of autism.
- Survey data is filled out truthfully. The research must be based on authentic and reliable data; otherwise, subsequent analysis and conclusions will be problematic.
- The survey data is representative. Only with a representative sample can the research findings be generalized to the entire population of autistic children. This is a prerequisite for the validity of the study.
- Autistic children exhibit homogeneity. Compared to other neurodevelopmental disorders, autistic children do exhibit a degree of homogeneity in certain core symptoms, which can simplify research design and analysis.
- The social skills of autistic children are primarily influenced by individual cognition; the influence of family, society, and other environmental factors is not considered. While environmental factors do influence the development of social skills in autistic children, individual cognitive abilities are likely the most critical influencing factor. Focusing on individual cognitive factors benefits the research emphasis.

4. Symbol conventions

This section defines key mathematical notations used throughout the study to ensure clarity and consistency in model formulations. Symbols are categorized by their primary context of use.

- General Variables

1. x_i: Cognitive characteristic score
2. y_i: Social skill score
3. D: Set containing cognitive characteristics and social skills (dataset)

- Neural Network Model

4. h_i: The ii-th hidden layer
5. w_i: The ii-th weight
6. b_i: The ii-th bias
7. θ: Model parameters

- Multiple Linear Regression Model

8. β_0: Intercept
9. β_1 , β_2, ..., β_n: Coefficients of the independent variables
10. ϵ: Error term

- Grey Relational Analysis Model

11. $x_i{}'$: Min-Max normalized value of the ii-th raw data point
12. $min(X)$: Minimum value in the raw dataset
13. $max(X)$: Maximum value in the raw dataset
14. ρ: Grey relational degree resolution coefficient

5. Data collection

Prior to model building, group members distributed questionnaires to autism support organizations and collected data from 73 autistic individuals, quantifying their social characteristics. The questions in the distributed questionnaire are listed below:

We quantified items from the questionnaire to derive the corresponding cognitive characteristics: attention process, cognitive representation process, behavior generation process, motivation process, motivation. For items 8-13, the group calculated the autistic individuals' social skill score by taking the average. Cognitive characteristics were used as model inputs, and the social skill score as the model output, written into the dataset.

6. Model establishment

The purpose of model establishment in this study is: To predict the social skills of the autistic population based on their cognitive characteristics, and to provide new insights for improving the social skills of autistic individuals by exploring the relationship between the two.

6.1. Neural network model

The research problem involves the relationship between the social characteristics of the autistic population and their social skill scores. Since the model involves autism and no quantitative relationship between variables can be currently established, questionnaires were distributed, and machine learning was used to explore variable relationships and predict the social skill scores of autistic individuals.

This study employs a neural network machine learning method to predict the relationship between the cognitive characteristics of autistic individuals and their interpersonal skill scores.

6.1.1. Dataset creation

We use the Dataset: $D = \{(x_i, y_i)\}_{i=1}^{n}$

Where $x_i \in R^d$ refer to the input feature vector, and $y_i \in R$ is the target vector, i.e. cognitive characteristic scores and interpersonal skill scores. The dataset was split into training and test sets in a ratio.

$$D_{train} \in \{(x_i, y_i)\}_{i=1}^{n} \tag{1}$$

$$D_{val} \in \{(x_i, y_i)\}_{i=1}^{n} \tag{2}$$

Satisfying,

$$D_{train} \cap D_{val} = \emptyset \ where \ \{ \begin{matrix} D_{train} = \{(x_i, y_i)\}_{i=1}^{n} \\ D_{val} = \{(x_j, y_j)\}_{j=n+1}^{n+m} \end{matrix} \tag{3}$$

6.1.2. Building the neural network

Python code was used to build a neural network with the architecture x×16×16×1. The input layer $x \in R^d$ serves as the input feature vector. Hidden Layer 1 consists of 16 neurons:

$$h_1 = ReLU(w_1 x + b_1) \tag{4}$$

Where activation weights $w_1 \in W^{x \times 16}$, activation bias $b_1 \in B^{16}$.

Hidden Layer 2 also consists of 16 neurons:

$$h_2 = ReLU(W_2 h_1 + b_2) \tag{5}$$

Where activation weights $w_2 \in W^{16\times16}$, activation bias $b_2 \in B^{16\times16}$.

The output layer consists of one neuron outputting the predicted value:

$$\hat{y} = w_3^{\top} h_2 + b_3 \tag{6}$$

Where activation weights $w_3 \in W^{1\times64}$, activation bias $b_3 \in B^{1\times1}$.

During our experimentation, we found that changing the activation function to sigmoid or $tanh$ increased MAE and MSE by 5 and 15, respectively.

$$\sigma(x) = \frac{1}{1+e^{-x}}, tanh\,(x) = \frac{1-e^{-2x}}{1+e^{-2x}} \tag{7}$$

Therefore, the $ReLU$ function was used for both hidden layers:

$$ReLU(x) = max(0, x) \tag{8}$$

6.1.3. Setting hyperparameters and setting loss function

Learning Rate: Fixed at 0.1 for training epochs $\leq$ 5. For training epochs $>$ 5, the learning rate decreases exponentially based on the number of epochs:

$$LR(epoch) = \begin{cases} 0.1 & if\ epoch < 5 \\ 0.1 \cdot exp(\,0.1(5 - epoch)) & if\ epoch \geq 5 \end{cases} \tag{9}$$

Mean Squared Error (MSE) was used as the loss function for model training.

6.1.4. Training the model

The model takes the feature vector as input and the interpersonal skill score as output. Model parameters (activation weights W and activation biases B) are updated by minimizing the loss function MSE on the validation set:

$$\theta_{predict} = argminlimits_{\theta} \frac{1}{n} \sum_{i=1}^{n} \mathcal{L}\left(y_{train}^{(i)}, y_{predict}\left(\theta; x^{(i)}\right)\right) \tag{10}$$

6.1.5. Model evaluation

Mean Squared Error (MSE) and Mean Absolute Error (MAE) were used to evaluate model performance:

$$MSE = \frac{1}{n} \sum_{i=1}^{n} (\, y_i - \hat{y}_i)^2 \tag{11}$$

$$MAE = \frac{1}{n} \sum_{i=1}^{n} |\, y_i - \hat{y}_i | D_{val} \in \{(x_i, y_i)\}_{i=1}^{n} \tag{12}$$

6.1.6. Visualization

Line charts were used to visualize changes in MSE and MAE during training. Scatter plots y_i, $\hat{y}_i$ and frequency distribution histograms of errors $e_i = y_i - \hat{y}_i$ were used to visualize model predictions.

6.1.7. Calculating coefficient of determination $\boldsymbol{R^2}$

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(\, y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(\, y_i - \bar{y})^2} \tag{13}$$

Where $\bar{y}$ is the mean of the actual values.

After predicting the relationship between autistic cognitive characteristics and interpersonal skills using the neural network, we employed Multiple Linear Regression and Grey Relational Analysis models to explore the associations between individual cognitive characteristics and interpersonal skills.

6.2. Multiple linear regression model

We used a multiple linear regression model to study the linear relationship between the cognitive characteristics of the autistic population (attention process, cognitive representation process, behavior generation process, motivation process, motivation) as independent variables x_i, and interpersonal skills as the dependent variable y.

6.2.1. Mathematical model

Based on the fundamental assumptions of linear regression, assuming a linear relationship between and y, the mathematical model can be expressed as:

$$y = \beta_0 + \beta_1 x + \beta_2 x^2 + \epsilon \tag{14}$$

Where:

1. y is the dependent variable (Interpersonal Skills);
2. $x_1, x_2, \ldots, x_n$ are independent variables (attention process, cognitive representation process, behavior generation process, motivation process, motivation);
3. β_0 is the intercept;
4. $\beta_1, \beta_2, \ldots, \beta_n$ are the coefficients of the independent variables;
5. ϵ is the error term.

6.2.2. Model training and model evaluation

The dataset was split into training and test sets. The linear regression model was fitted using the training set, i.e., solving for the parameters β that best fit the training data.

After training, the model's performance was evaluated using the test set. Metrics such as Mean Squared Error (MSE), Coefficient of Determination (R^2), and Mean Absolute Error (MAE) were calculated to assess predictive ability.

A scatter plot of actual values vs. predicted values was created to visualize model performance. Ideally, points should cluster around a line with slope=1, indicating agreement between predicted and actual values.

6.3. Grey relational analysis model

Due to poor fitting performance in the multiple linear regression model, the group hypothesized that there might not be a clear linear relationship between the cognitive characteristics of the autistic population and their interpersonal skill scores. Therefore, Grey Relational Analysis (GRA), a data analysis method suitable for small datasets, was employed to study the degree of association between cognitive characteristics (attention process, cognitive representation process, behavior generation process, motivation process, motivation) and interpersonal skills.

6.3.1. Data preprocessing

Given a raw dataset $X = \{x_1, x_2, \ldots, x_n\}$, the Min-Max normalized dataset $X' = \{x_1{}', x_2{}', \ldots, x_n{}'\}$ was calculated using:

$$x_i{}' = \frac{x_i - min(X)}{max(X) - min(X)} \tag{15}$$

Where:

$x_i{}'$ is the Min-Max normalized value of the ii-th data point;
x_i is the i-th data point in the raw dataset;
$min(X)$ is the minimum value in the raw dataset;
$max(X)$ is the maximum value in the raw dataset;
This processing ensures data falls within a uniform numerical range [0,1].

6.3.2. Grey relational coefficient calculation

The grey relational coefficient $\gamma i(k)$, defining the association between the comparison sequence and the reference sequence at a specific point k, is calculated as:

$$\xi_i(k) = \frac{\min_i \mathrm{m}_k \,|\, (k) - x_i(k)| + \rho \cdot \max_i \mathrm{m}_k \,|\, (k) - x_i(k)|}{|x_0(k) - x_i(k)| + \rho \cdot \max_i \mathrm{m}_k \,|\, (k) - x_i(k)|} \tag{16}$$

Where:

$x_0(k)$ is the reference sequence (Interpersonal Skills);
$x_i(k)$ is the ii-th comparison sequence (attention process, cognitive representation process, behavior generation process, motivation process, motivation);
ρ is the resolution coefficient, set to 0.5 in this study;
min and max represent the global minimum and maximum differences across all sequences and points.

6.3.3. Calculating grey relational degree

The grey relational degree for each feature was calculated by averaging the coefficients.

The calculated Grey Relational Degrees are ranked. Cognitive characteristics with higher rankings are identified as key influencing factors. Finally, bar charts are used to visualize the grey relational degrees of the selected features for further analysis and understanding of the degree of association.

7. Model solution

Dataset Preparation: Questionnaires were distributed to autism support groups in the community, collecting data on social characteristics and corresponding descriptions of interpersonal skills. Group members calculated the interpersonal skill score by averaging the scores from the interpersonal skill description items.

7.1. Neural network model

7.1.1. Model training

Group members used social characteristics as model inputs and interpersonal skill scores as outputs for neural network training. It was observed that MAE and MSE stopped decreasing around epoch=60, so the training epoch was set to 80.

7.1.2. Training process evaluation

MSE and MAE were used to evaluate model performance during training. It was observed that in the early training phase (epoch ≤ 20), MSE and MAE fluctuated significantly but showed an overall downward trend. In the middle phase ($20 < \text{epoch} \leq 40$), MSE and MAE fluctuated but remained relatively flat overall. In the later phase (epoch > 40), MSE and MAE stabilized. The final MSE was 166 and MAE was 9.8. The line charts visualizing MSE and MAE changes are shown below (see Figure 1 and Figure 2).

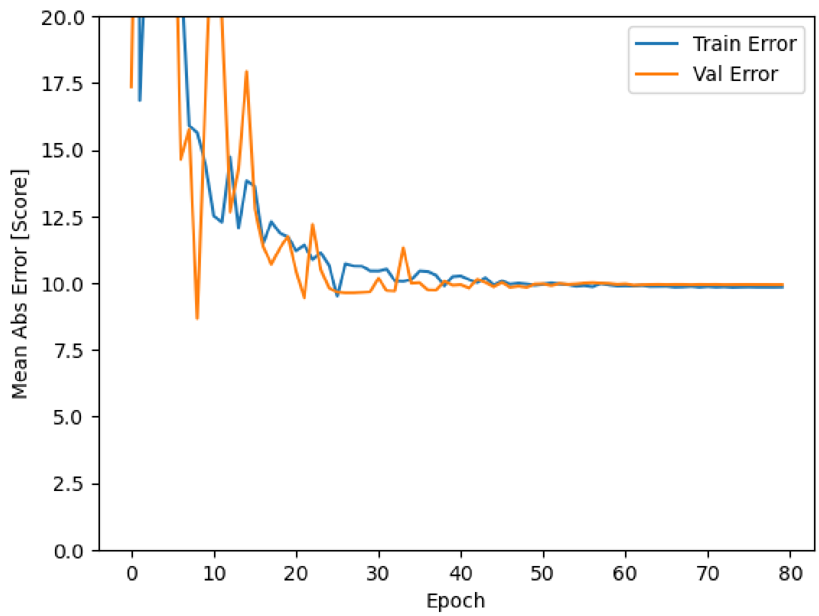

Figure 1. Training and validation MSE trends across epochs

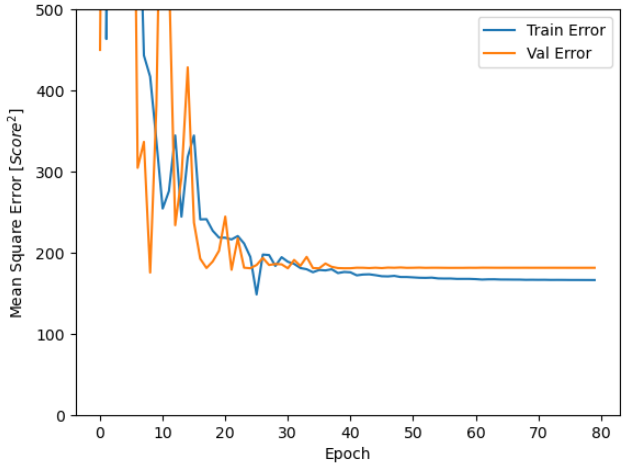

Figure 2. Training and validation MAE trends across epochs

7.1.3. Model test evaluation

The test set and coefficient of determination were used to evaluate model performance. On the 9 samples in the test set, the model's average prediction error was 9.98. A scatter plot comparing model predictions and true values is shown below (see Figure 3).

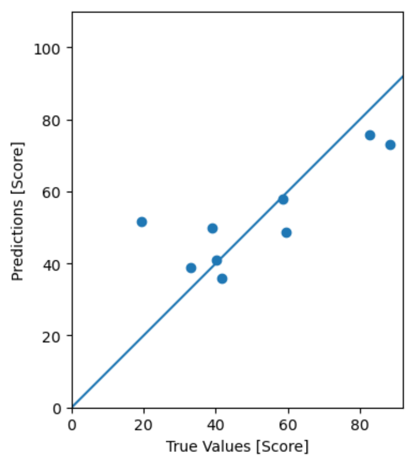

Figure 3. Predicted vs. Actual social skill scores scatter plot

7.1.4. Coefficient of determination evaluation

Substituting the prediction data into the R^2 formula yielded a value of 0.80639, indicating that the model fit was relatively successful.

7.2. Multiple linear regression model

After model training, the `model.predict(X_test)` method was used to predict the test set features, obtaining predictions y^. Using y^ and the true target values y_{test}, MSE, R^2, and MAE were calculated as performance metrics. The parameters (coefficients) and intercept of the linear regression model were printed. The results are shown below (see Figure 4).

Mean Squared Error: 6137.869861875643
R^2: 0.042700304211402584
Mean Absolute Error: 54.74593044769049
Coefficients:
0.21333172 Attention Process

2.32687236 Cognitive Representation Process
0.42033247 Behavior Generation Process
0.22584012 Motivation Process
1.11550035 Motivation
Intercept: 5.370304362681054

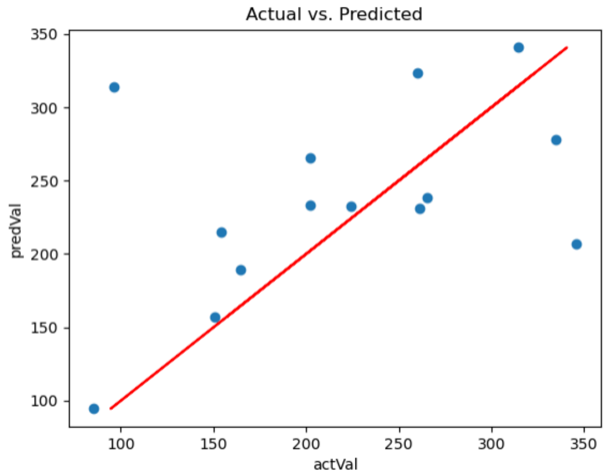

Figure 4. The result of cognitive features in linear regression

7.3. Grey relational analysis model

Data was read and preprocessed. The grey relational degree between each feature and the target feature was calculated. Features were ranked based on their grey relational degree, and the top features were selected as input features. The results are shown below (see Figure 5).

Grey Relation Scores:
Attention Process: 0.6319
Cognitive Representation Process: 0.6567
Behavior Generation Process: 0.6543
Motivation Process: 0.6663
Motivation: 0.6512

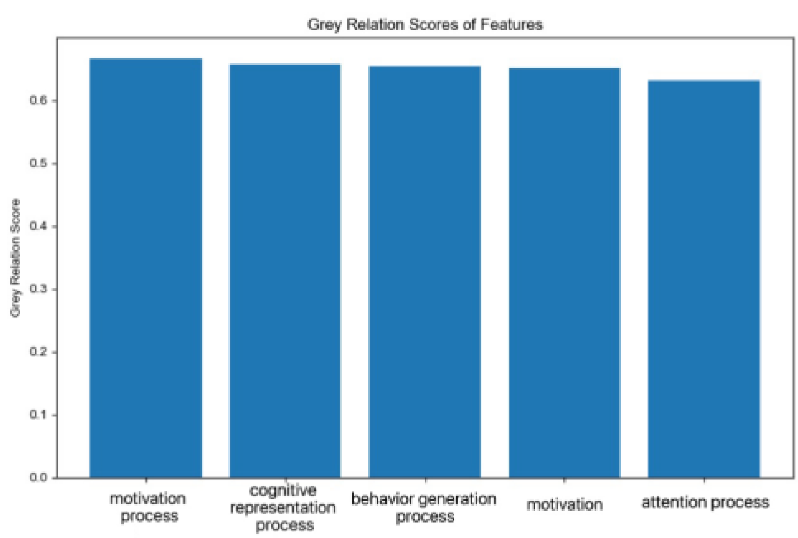

Figure 5. Grey relational scores of cognitive features

8. Model validation and analysis

8.1. Neural network model

The MSE and MAE charts show that the neural network's Mean Squared Error stabilized around 166, and the Mean Absolute Error stabilized around 9.8. The model had relatively many outliers. According to model evaluation tests, the coefficient of determination R^2 was 0.80639, indicating a relatively good model fit. The model can directly predict the social skills of out-of-sample autistic children based on cognitive characteristics, facilitating the assessment of autism treatment progress. However, due to the small dataset size, the model's applicability is limited. Furthermore, data collection relied on questionnaires, introducing potential subjective bias, which may explain why MSE and MAE did not reach lower levels during neural network fitting. There is significant room for optimization.

8.2. Multiple linear regression model

Cognitive characteristics and social skills in autism typically involve multiple influencing factors. The multiple linear regression model allows for the simultaneous quantitative assessment of the impact of multiple independent variables on the dependent variable. This model is simple, easy to implement, and its results are highly interpretable, providing an intuitive reflection of the contribution of each cognitive characteristic to social skills. The sensitivity analysis (controlling variables) for each cognitive feature in the linear regression model is visualized below (see Figure 6). It is evident that the cognitive representation process has the highest sensitivity score, significantly higher than other factors. This indicates that the cognitive representation process has the greatest impact on the model output and is the most sensitive factor. motivation also has a relatively high sensitivity score, indicating it is also a significant influencing factor. Other factors (attention process, behavior generation process, motivation process) have lower sensitivity scores, suggesting their impact on the output is relatively minor. Therefore, these factors (Cognitive Representation and motivation) warrant primary focus in model optimization or decision-making. Based on the training results, the linear regression model performed poorly on the current dataset, evidenced by the low R2 value (only 0.0427), high MSE (6137.87), and substantial MAE (54.75). The large MSE and MAE indicate significant deviation between the model's predictions of the target variable (social skills of autistic children) and reality. This may be due to the small sample size or subjective factors in questionnaire responses. Consequently, the linear model could not effectively fit the data under the current circumstances and lacked precise predictive power. Based on this analysis, we infer that the relationship between the cognitive characteristics and social skills of autistic children may not be linear.

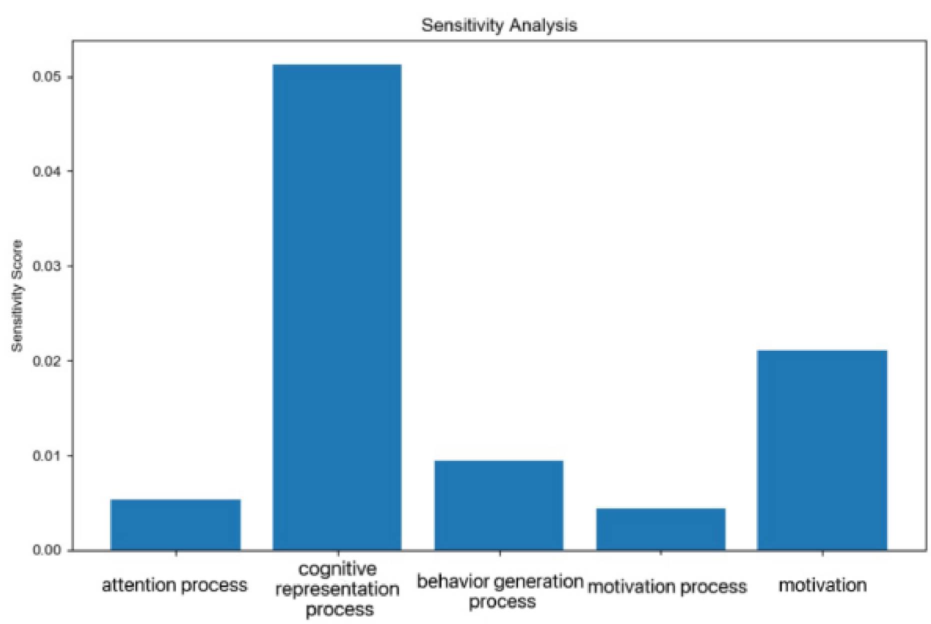

Figure 6. Sensitivity analysis of cognitive features in linear regression predictions

8.3. Grey relational analysis model

Grey relational analysis does not directly analyze sensitivity; it is used to identify and rank the main factors influencing the system. Due to the small data volume, the applicability and accuracy of all models are limited. No linear relationship between autistic cognitive characteristics and social skills was found; only associations were discovered, introducing uncertainty for formulating intervention measures. There is significant room for optimization.

9. Conclusion

This study, through in-depth analysis of the social cognitive characteristics and interpersonal skills of 73 autistic children, revealed varying degrees of influence of different cognitive characteristics on interpersonal skills. Results from the Grey Relational Analysis model showed that attention process, cognitive representation process, behavior generation process, motivation process, and motivation all exhibited a similar, moderate level of correlation with interpersonal skills. This suggests that improving the cognitive representation and behavioral motivation processes in autistic children may help enhance their interpersonal skills. Specifically, improving autistic children's ability to recognize errors and stimulating their interest in interacting with others could potentially boost their social abilities. Furthermore, although other social cognitive characteristics showed lower correlations with interpersonal skills, they might still have indirect effects on the children's social development. These findings provide an important basis for developing effective intervention strategies for autistic children in the future.

Despite yielding meaningful findings, this study has limitations. The current model's prediction accuracy needs improvement, evidenced by high MSE and MAE, and the failure to identify a linear relationship. These point towards limited predictive power. Based on the above findings, we propose the following recommendations and future research directions:

(1) Personalized Intervention Strategies: Develop personalized intervention programs targeting the key factors identified (attention process, cognitive representation process, behavior generation process, motivation process, motivation) to enhance the social cognitive abilities and interpersonal skills of autistic children.

(2) Multi-dimensional Assessment Models: Considering the limitations of existing models, future research should explore assessment models incorporating more variables and non-linear relationships to improve the accuracy of predicting interpersonal skills in autistic children.

(3) Longitudinal Tracking Studies: Conduct longitudinal studies to evaluate the long-term effectiveness of interventions and further understand the developmental trajectory of social skills in autistic children.

In conclusion, this study provides new perspectives and methods for understanding and assisting autistic children, demonstrating the influence of cognitive characteristics on social skill development and pointing towards potential directions for future research and practice. Through continued research and practice, we hope to create a more inclusive and supportive environment for autistic children, helping them maximize their personal potential.

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Appendix

Questionnaire for social cognitive characteristics and interpersonal skills assessment

- Demographic Information

  1. Child's Gender
     □ Male
     □ Female
  2. Child's Age
     __________ years

- Section B: Social Cognitive Characteristics
  (0 = Minimal expression, 100 = Maximal expression)

  3.attention process
  Does the child focus on specific things?
  0 (Does not focus) ———— 100 (Intensely focuses)
  4.cognitive representation process
  After parental correction, does the child recognize their own mistakes?
  0 (Unable to recognize) —— 100 (Fully recognizes)
  5. behavior generation process
  Does the child observe and imitate others' behaviors?
  0 (Never) —————— 100 (Very frequently)
  6.motivation process
  How do others' responses influence the child's repetition of behaviors?
  0 (No influence) ———— 100 (Strong influence)
  7.motivation
  Is the child interested in communicating with others?
  0 (Not interested) ——— 100 (Very interested)

- Section C: Interpersonal Skills
  (0 = Minimal ability, 100 = Maximal ability)

  8.Response to Verbal Calls
  0 (No response) ————— 100 (Always responds)
  9.Verbal Expression Ability
  0 (No speech) ————— 100 (Fluent speech)
  10.Facial Expression & Body Language Communication
  0 (Deficient) ————— 100 (Good skills)
  11.Social Interaction Skills
  0 (Deficient) ————— 100 (Good skills)
  12.Emotional Expression & Regulation
  0 (Unable) —————— 100 (Accurately expresses/regulates)
  13.Ability to Establish/Maintain Friendships
  0 (No desire) ————— 100 (Able to sustain friendships)