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RESEARCH

Profiling Chinese children with symptoms of SpLD, ADHD, or ASD: a transdiagnostic and biopsychosocial study

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Abstract

Background Specific learning difficulties (SpLD), ADHD, and ASD are the most common neurodevelopmental disorders (NDDs) found in mainstream schools. In addition to formal NDD diagnoses, children may exhibit NDD symptoms without meeting full diagnostic criteria, and heterogeneities and commonalities are frequently observed regardless of whether children have been diagnosed or not, raising concerns about the lack of inclusive support for all. Following the transdiagnostic approach and biopsychosocial model, this study aims to cluster and profile children with these symptoms via cognitive, psychological, and ecological factors, using an unsupervised machine learning algorithm.

Methods Based on parent-report checklists, 267 Chinese primary school children in Grades 1–4 with at least one type of NDD symptoms were identified (164 boys; age in months: $M = 102$, $SD = 17.30$) from a bigger dataset ($N = 1{,}034$). A typically developing (TD) control group was created and matched with the NDD group in terms of age, gender, nonverbal IQ, and family socioeconomic status (SES). By using exploratory and confirmatory analyses, executive functioning, visual processing, and linguistic skills were extracted as cognitive factors, while internalising problems, externalising problems, positive child-parent relationships, and negative child-parent relationships were extracted as psychological and ecological factors.

Results K-means clustering based on the seven extracted core factors identified five distinct clusters. Three clusters exhibited specific cognitive weaknesses, while the other two mainly showed psychosocial problems. Two severe-symptom groups (i.e., the Linguistic Difficulties group and the Psychosocial Difficulties group) also demonstrated worse academic and mental health outcomes.

Conclusions Our findings demonstrate the potential to focus on symptoms beyond diagnostic labels, as well as the inclusion of psychosocial factors alongside cognitive ones, thereby contributing to the design of more targeted and

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comprehensive support for children with special education needs and informing current inclusive education practice in China.

Clinical trial number Not applicable.

Keywords Neurodevelopmental disorders, Machine learning, Special education needs, Inclusive education

Introduction

Neurodevelopmental disorders (NDDs) are defined as conditions primarily associated with disruptions in the neurological system, resulting in functional difficulties that may vary from specific to global areas of development [1]. Researchers estimate that NDDs affect approximately 15% of children and adolescents worldwide [2] and account for over 50% of special educational needs (SEN) in mainstream schools [3]. Of those, specific learning disabilities (SpLD), attention-deficit/hyperactivity disorder (ADHD), and autism spectrum disorder (ASD) are the most prevalent of these types [4]. Narrowing down to China, as an example, these three NDDs account for 80–90% of reported SEN cases in mainstream schools in Hong Kong [5], prompting calls for deeper research to identify the most effective support strategies for students with SEN.

This study had two focuses. First, it adopted a transdiagnostic perspective to reflect the limitations of current taxonomy-based diagnostic systems, in response to global calls for the development of inclusive education [6]. Second, it applied a biopsychosocial view to integrate psychosocial factors that have often been neglected alongside the cognitive indicators.

A critical issue in understanding children with NDDs is the heavy reliance on diagnostic labels. Recent reviews asserted that this approach fails to address the complexity of NDDs in reality (e.g., [7]). For example, children with ASD also show various language-related challenges and differences in cognitive functioning and sensory processing [8–10], ADHD presents a diverse array of etiological factors and clinical profiles [11], and SpLD is also highly heterogeneous [12]. Importantly, the significant overlap across NDDs (ranging from 15% to 70%;[12, 13]) suggests that the current diagnostic classifications struggle to capture the full complexity of children with comorbid NDD symptoms. Similar to the findings worldwide, recent studies in Chinese children also revealed that the symptoms and relevant cognitive factors (e.g., executive functioning) and noncognitive factors (e.g., family environment) of SpLD, ADHD, and ASD are tightly associated [14–17].

Practitioners also expressed a similar concern that the existing diagnosis system does not adequately reflect a child's specific needs [18, 19]. Rather than focusing on labels like ADHD or ASD, teachers often prioritise the individual traits of those with distinct SENs (e.g., emotional issues, communication challenges, learning difficulties) and tailor their support accordingly. Therefore, a transdiagnostic approach can advance current research by providing a symptom-focused solution in practical settings [7].

Moreover, children showing NDD symptoms but lacking a formal diagnosis often go unnoticed, resulting in inadequate support and resources in school and community contexts [20]. The global prevalence rates of SpLD, ADHD, and ASD have been recorded as around 10%, 7.6%, and 2.3%, respectively [1, 21, 22], but earlier studies showed that over 50% of children worldwide could not achieve minimum proficiency levels in reading and mathematics (two aspects of SpLD) [23], and around 25% of 15-year-olds encountered learning difficulties [24]. A possible reason for this discrepancy is that NDDs run on a severity continuum [25–29], whereby children are diagnosed only when certain difficulties are severe enough to meet the cut-off, while others with relatively mild symptoms do not receive sufficient attention. Instead, a transdiagnostic approach can identify children with NDDs even when they do not fit neatly into traditional diagnostic categories.

The second focus of this study was the application of the biopsychosocial model, which is incorporated into the framework of the International Classification of Functioning, Disability and Health (ICF) [30]. During the development of special and inclusive education, three major models have been established, namely the medical, social, and biopsychosocial models [31]. The medical model concentrates on impairments and the underlying pathological mechanisms, and the social model highlights that the challenges faced by disabled individuals are predominantly due to societal barriers. Instead, the biopsychosocial model offers a more ecologically valid view, bridging the gap between the former two models by considering the multifaceted nature of health conditions. In particular, it advocates treating the influences and consequences of a "disease" as substantial components to provide a holistic understanding and support to individuals with difficulties, an objective that can hardly be achieved if NDDs research only focuses on (neuro)cognitive impairments and corresponding behavioural consequences [32, 33].

The biopsychosocial model also aligns well with the context of inclusive education, as previous research has shown a close relationship between SpLD, ADHD, and

ASD symptoms and psychosocial factors. In particular, some symptoms have been associated with poor parenting and/or temporal psychological problems [34–39]. Within the medical model framework, a critical function of (trans)diagnosis is to explore the pathological causes of NDDs at neurocognitive levels. In contrast, the biopsychosocial model examines children's profiles within a macrosystem, exploring how their challenges emerge through the dynamic interplay of the neurocognitive, psychological, and environmental factors, and seeks targeted solutions by addressing the interactions among them, thereby demonstrating greater ecological validity.

Building on these two frameworks, the present study examined the profiles of children with NDD symptoms using k-means clustering, a commonly employed unsupervised machine learning algorithm that has demonstrated promise in recent NDD studies [32, 40]. In the cognitive domain, executive functioning factors were examined because general cognitive architecture has been considered critical in predicting various cognitive difficulties [41]. Several linguistic skills, which are critical predictors of NDDs [42], were also included. Visual processing factors were included because they are important skills for Chinese children's learning, given the logographic properties of the Chinese orthography [43]. In the psychosocial domain, we adopted the Strengths and Difficulties Questionnaire (SDQ) to cover internalising and externalising problems [44], and child-parent relationships were measured to reflect family influence, which is fundamental for child development [45] and relates to NDD symptoms in early childhood [38].

The factor dimension was reduced when controlling for demographic variables of age, nonverbal IQ, and family socioeconomic status (SES). The identified clusters were compared with each other and with a control group on critical factors and additional learning and well-being outcomes to validate and refine the profiles. The relationships between individual predictive factors and learning and well-being outcomes have been demonstrated in Chinese children. For example, linguistic skills have been shown to significantly predict subsequent word reading and reading comprehension performance in longitudinal studies [46, 47]. Researchers also found an association between negative parenting styles and children's well-being [48]. Therefore, the inclusion of these additional outcomes in post-hoc analyses could help further illustrate the profiles of the identified clusters (e.g., which clusters exhibit the most severe symptoms and outcomes that warrant attention).

Contrary to the traditional view of a one-to-one correspondence between cognitive impairments and diagnostic labels, we expected that both cognitive and psychosocial factors would contribute to the identification of clusters, with children exhibiting NDD symptoms being divided into different clusters based on their symptom patterns rather than diagnostic labels.

Method

Sample

A total of 1,034 participants were recruited from Grades 1 to 4 of a primary school in Guangdong, China (Grade 1: $n = 257$, mean age = 6.98, $SD = 0.67$; Grade 2: $n = 258$, mean age = 8.21, $SD = 0.63$; Grade 3: $n = 253$, mean age = 9.03, $SD = 0.57$; Grade 4: $n = 266$, mean age = 10.41, $SD = 0.79$). Based on parents' reports on the checklists, an NDD sample ($n = 267$, 25.8% of the entire sample) was identified. A matched typically developing (TD) control ($n = 267$) was also selected. All participants were native Chinese speakers. Children provided verbal consent before testing, and they were informed that they could withdraw at any time if they wished to do so. Written informed parental consent was also collected. This study was approved by the Human Research Ethics Committee of the Education University of Hong Kong and conformed to the Declaration of Helsinki. This research was not preregistered with an analysis plan in an independent, institutional registry.

The NDD sample was identified based on three commonly used parent-report checklists. ADHD was evaluated using the Chinese version of the Nolan, and Pelham Rating Scale, Fourth Edition (SNAP-IV) [49, 50], which consists of 26 items on a four-point scale (ranging from 0 = not at all to 3 = very much). The inattention and hyperactivity-impulsivity sub-scores were calculated. A score of 13 or higher in either subscale indicates an ADHD symptom. The Cronbach's alpha coefficients were 0.89 and 0.87, respectively. SpLD in reading, writing, dictation, and mathematics was evaluated using 26 items on a five-point scale (ranging from 1 = never to 5 = often). These items were based on the Hong Kong Behaviour Checklist of Specific Learning Difficulties in Reading and Writing for Primary School Students, Second Edition (BCL-P[II]), available at https://hksld.eduhk.hk [51]. Children were identified as having SpLD symptoms if their parents reported 14 or more items as "sometimes" or "often". The Cronbach's alpha was 0.97. ASD was measured via the Chinese version of the Childhood Autism Spectrum (CAST) [52, 53]. There are 37 yes/no questions regarding children's behaviours and abilities indicative of ASD, with each yes answer coded as one point. The cutoff is 15. The Cronbach's alpha was 0.82.

In summary, the children in the NDD sample were at risk of ADHD ($n = 159$), SpLD ($n = 149$), and/or ASD ($n = 48$). We also categorised them into seven NDD types according to comorbidity (see Supplementary Table 3). Nearly 1/3 of them (81 out of 267) had displayed more than one NDD symptom. A summary of children with formal diagnosis histories can be found in Appendix 1.

After identifying 267 children at risk of NDDs, we created a TD control group by sampling the remaining 767 children (i.e., 1,034–267 = 767) to match the distribution/count of demographic covariates (i.e., age, gender, nonverbal IQ, and family SES) and the sample size, using the "optimal" method in the R package *MatchIt* [54]. Nonverbal IQ was measured via the 's Standard Progressive Matrices (SPM) [55, 56]. Family SES was evaluated based on parental education (ranging from 1 = completed primary school to 8 = completed doctoral studies) and occupation (ranging from 1 = unemployed/unskilled work to 5 = senior managerial/senior professional work). We conducted a principal component analysis (PCA) based on standardised scores of the above two. Only one component had an eigenvalue exceeding 1, explaining 59.42% of the variance, which was used as the family SES index. This matching process yields a TD control that has similar demographic characteristics and the same sample size as the NDD sample (i.e., 267 sampling from 767) (see Supplementary Fig. 1).

Measures

Executive functioning (EF)

The Stroop task, which assesses the inhibitory control aspect of EF, was performed using paper-printed materials [57]. The child was asked to read five Chinese words (Sect. 1) and name five corresponding colours in circles (Sect. 2), which were shown for practice before the formal testing. Feedback was provided when needed. Sections 3–4 were the baseline condition, in which the child named 20 colourful circles as fast as possible, and incorrect responses could be corrected immediately. Sections 5–6 were the congruent condition in which the child named the colours of 20 colour words that matched the colours for each section. In contrast, Sects. 7–8 were the incongruent condition. The response time was calculated as $T_{incongruent} - (T_{baseline} + T_{congruent})$, and the error penalty was considered. The Cronbach's alpha was 0.85.

Working memory was assessed via a backward digit span task from the Automated Working Memory Assessment [58]. The child was asked to repeat a digit string presented orally, backwards, by the experimenter. The strings started at two digits and gradually increased to nine. There were 14 strings, with one point for each correct answer. The Cronbach's alpha was 0.76.

Linguistic skills

Rapid automatised naming speed was assessed by asking the child to read aloud 40 single-digit numbers presented in a 5 × 8 array on a printed piece of paper as quickly as possible [59]. There were five numbers (i.e., 1, 2, 5, 6, and 8) on each row arranged in a random order. The child completed this task twice, and the average time was calculated.

Vocabulary knowledge was assessed by asking the child to explain the meaning of orally presented words [60]. There were 30 Chinese words ordered by difficulty level. Responses were rated as 0 (unrelated/no response), 1 (partial explanation), or 2 (proper explanation). The Cronbach's alpha was 0.82.

Morphological awareness was assessed by orally presenting a target word following two alternative words and asking the child to select the word with a Chinese character sharing its meaning [61]. There were 31 target words, and one point was given for each correct answer. The Cronbach's alpha was 0.64.

Phonological awareness was assessed with 29 syllable deletion items and 22 onset deletion items [62]. For each syllable deletion item, the child was asked to remove a syllable from a three-syllable word. For each onset deletion item, the child was asked to remove the onset of a syllable. One point was given for each correct answer. The Cronbach's alpha was 0.85.

Visual processing

Visual-motor integration (VMI) was assessed via items 13–27 from the Beery-Buktenica Developmental Test of Visual-Motor Integration, Sixth Edition [63]. The children were asked to reproduce geometric figures with increasing difficulty using a pencil and paper. One point was given for each correctly reproduced figure, and the scoring ended after three consecutive errors. The Cronbach's alpha was 0.79.

A 15-item mental rotation task was used to assess the spatial reasoning and visual-spatial processing ability [64]. The children were shown a target image alongside four optional images (i.e., two rotated images and two mirror-rotated images). They were asked to circle the two rotated images that matched the target. One point was only given for each item if both correct options were selected. The Cronbach's alpha was 0.76.

Psychological difficulties

The Chinese version of the Strengths and Difficulties Questionnaire (SDQ) was used to assess parent-reported child mental health problems [44, 65]. The SDQ comprises five subscales, each consisting of five questions on a three-point scale (ranging from 0 = not true to 2 = certainly true). The Cronbach's alpha of the scale was 0.68.

Following Goodman et al. [66], the emotional and peer subscales were treated as indicators of internalising problems, the behavioural and hyperactivity subscales were treated as indicators of externalising problems, while the prosocial subscale does not belong to either internalising or externalising problems. In the current study, the four individual subscale scores (except for the prosocial subscale scores) were included in the factor extraction process before clustering to minimise information loss and verify Goodman's two-dimensional category in our NDD sample (see Supplementary Table 1). In post-hoc analysis, the internalising and externalising composite scores were used to illustrate a concise pattern for generalisation.

Child-parent relationships

The short-form Chinese version of the Child-Parent Relationship Scale (CPRS) was used. This is a 15-item parent-report tool on a five-point Likert scale (from 1 = definitely does not apply to 5 = definitely applies) assessing relational conflict and closeness [67, 68]. The conflict and closeness sub-scores were calculated. The Cronbach's alpha was 0.73.

Child-parent relationships were also evaluated via parenting styles using the Chinese version of the 23-item short form of the Egna Minnen Beträffande Uppfostran (EMBU) questionnaire [69, 70]. The children's parents rated 23 statements related to three aspects of parenting on a five-point scale (ranging from 1 = strongly disagree to 5 = strongly agree). The rejection, emotional warmth, and over-protection sub-scores were calculated. The Cronbach's alpha was 0.74.

Additional learning and mental health outcomes

The identified clusters would be further compared on several learning and well-being outcome measures. Chinese character reading was assessed using 100 Chinese character items arranged in ascending difficulty order [43]. Children were asked to read characters individually and received one point for each correct answer. The test was terminated when the child received zero points on 15 consecutive items. The Cronbach's alpha was 0.98.

Reading fluency was assessed by asking the child to read as many common Chinese words as possible within 45 s [43]. There were 104 items shown on paper, including 21 single-character words, 76 two-character words, 5 three-character words, and 2 four-character words. The total number of correct responses was recorded.

Reading comprehension was assessed using some commonly used Chinese comprehension items that assess sentence-level (five multiple-choice items) and discourse-level understanding (short narrative and expository texts, six multiple-choice items for each text, twelve in total) (for recent studies, see [71, 72]). Each correct answer was given one point. The Cronbach's alpha was 0.75.

The children's health-related quality of life was assessed via the Pediatric Quality of Life Inventory (PedsQL), Version 4.0 [73]. We utilised a parent-reported version suitable for children aged 8–12, rating on a five-point Likert scale (0 = never, 4 = almost always). This measures physical, emotional, social, and school functioning difficulties during the previous month. Four sub-scores were calculated, with lower scores indicating fewer problems. Cronbach's alpha was 0.92.

Procedure

Data were collected during the spring semester. To align with the school's schedule and ensure the overall efficiency of testing, the VMI, reading comprehension, and nonverbal IQ tasks were administered collectively in each class. All other tasks were administered on an individual one-on-one basis. The experimenters were college students recruited from a local university and were well-trained before the investigation. Parents were invited to fill in the questionnaires at home.

Data analysis

Missing data were imputed in SPSS (version 28.0.1.0) before formal analysis. The performance of k-means could be affected in high-dimensional data when the sample size is limited (e.g., yielding less stable, interpretable results). Therefore, dimension reduction is necessary to identify a smaller number of key constructs that represent children's profiles. To achieve this, we conducted exploratory factor analysis (EFA) and confirmatory factor analysis (CFA) to extract a few core factors (composite scores) from seventeen individual cognitive and psychosocial indicators, using SPSS (version 28.0.1.0) and EQS (version 6.4), respectively. These core factors were regressed on control variables and then standardised for clustering. Then, by using the *scikit-learn* package (version 1.6.0) in Python (version 3.10), we ran k-means 1000 times with different centroid seeds, and the final model is the best output of consecutive runs. When using k-means, it is difficult to determine the optimal number of clusters in transdiagnostic research. One possible reason is that boundaries between clusters in a transdiagnostic sample can be fuzzy, while most clustering algorithms are designed to detect hard borders with clear boundaries between putative subgroups [7]. In this case, strictly adhering to statistical indices may yield statistical "best" output, but model interpretability and theoretical contributions could be limited. Therefore, researchers have often defined the number of clusters for exploratory purposes, with emphasis that the identified clusters should be theoretically relevant and have an adequate sample size for each group to allow for further validation and generalisation [32, 40, 74].

To determine the number of clusters, we calculated the gap statistics and silhouette scores from $k = 2$ to $k = 10$ and visualised them in elbow plots following the literature [40, 75–77]. The gap statistic for each k is calculated based on the within-cluster sum of squared errors (WSS), which reflects how well each data point is close to the centroid of the respective cluster for a given k. The gap statistic is calculated by comparing the difference in the log-WSS between the real data and a randomly generated data set, which should have a relatively low log-WSS since no clear cluster structure exists [78]. The maximum gap suggests the most distinct clustering structure for that *k*. The silhouette score for a sample is calculated by comparing the mean intra-cluster distance (*a*) and the mean inter-cluster distance (*b*). That is $(b - a) / max(a, b)$. This score ranges from 0 to 1, where a high score indicates that each data point is closer to its cluster compared to the nearest cluster [79]. To test the reproducibility stability, we also calculated the adjusted Rand index (ARI) with 1,000 bootstrapping resampling iterations for each *k*. ARI is a widely used external validation criterion that indicates the agreement of results when clustering is conducted repeatedly [80, 81], ranging from – 1 (worse than chance-level) to 1 (completely the same), with 0 indicating chance-level agreement.

We then performed Welch's ANOVAs to compare group differences in cognitive and psychosocial factors, as well as additional learning and mental health outcomes. Bonferroni's correction was used during multiple comparisons.

Results

Dimension reduction

The zero-order correlation matrix for the core factors involved in clustering demonstrated good intra-domain correlations in the cognitive and psychosocial domains (see Supplementary Fig. 2). By doing EFA with varimax rotation, we identified three factors in the cognitive domain (i.e., linguistic skills, EF, and visual processing), explaining 63.75% of the variance; two factors were identified in the psychological domain (i.e., externalising and internalising problems), which explained 72.04% of the variance; and two factors in the ecological domain (i.e., positive and negative child-parent relationships), explained 72.75% of the variance. The (rotated) component matrices are presented in Supplementary Table 1. CFA results suggested that the models fit the data very well (see Supplementary Table 2), and thereby the core factors for each domain were established. These factors were then regressed on age, nonverbal IQ, and family SES to control for covariate effects, and the standardised residuals were extracted to represent the adjusted factors.

Clustering

When considering statistical optimality, as indicated by elbow plots, silhouette scores suggested a two-cluster solution, whereas gap statistics suggested a three-cluster solution (see Supplementary Fig. 3). When k was larger than 5, gap statistics indicated less well-performing results, while silhouette scores indicated the model's performance increased. From $k = 2$ to 5, the ARI with a 95% CI was 0.58 (0.06, 0.93), 0.46 (0.17, 0.82), 0.41 (0.17, 0.73), 0.41 (0.21, 0.72), respectively. This indicates that, although the average ARI was relatively higher when k was smaller, the 95% CIs suggested concerning variability. We then further plotted the profiles of clusters from $k = 2$ to 5 to check model interpretability (see Supplementary Fig. 4). Differences in non-cognitive factors were found across clusters in all alternative models, thereby supporting the biopsychosocial model we adopted. Specifically, when $k = 2$, there was a simple high-and-low difference in the psychosocial dimensions, especially in SDQ INT, SDQ EXT, and CP NEG, while cognitive features were nearly identical between groups. When $k = 3$ and 4, some cognitive discrepancies were revealed, but the high-and-low pattern in the psychosocial aspect persisted. Instead, the five-cluster solution balanced the silhouette score, gap statistic, ARI, and interpretability, revealing comprehensive characteristics in both cognitive and noncognitive dimensions, and thereby became our final solution.

This five-cluster solution is shown in Fig. 1. The first three clusters have distinct cognitive profiles. Cluster 1 ($n = 61$ children out of 267, 22.85%) showed the worst linguistic abilities and the best visual abilities. Cluster 2 ($n = 56$, 20.97%) showed the worst visual processing but the best executive functioning, with very low scores on externalising problems and negative child-parent relationships (i.e., a good psychosocial profile). Cluster 3 ($n = 56$, 20.97%) showed the worst executive functioning and the best linguistic skills. We named them the Linguistic Difficulties (LD), Visual Difficulties (VD), and Executive Function Difficulties (EFD) groups, respectively. The remaining two clusters had average cognitive functioning but differed from others in the psychosocial domain. In particular, Cluster 4 ($n = 41$, 15.36%) showed severe internalising and externalising problems and negative child-parent relationships. Cluster 5 ($n = 53$, 19.85%) showed the highest level of externalising problems, while other psychosocial problems were at moderate or average levels, and the internalising problems score was especially low. We named them the Psychosocial Difficulties (PSD) and Behavioural Difficulties (BD) groups, respectively.

As shown in Fig. 2 (detailed information is provided in Supplementary Table 3), a significant portion of the NDD sample was distributed evenly among the five groups. Special relatedness was also found. That is, most children with SpLD-only were in the three cognitive-deficit groups (67 out of 82, 81.71%), while nearly two-thirds of the children with ASD symptoms were in the two psychosocial groups (15 out of 25, 60.00%).

Cognitive and psychosocial profiles

The cognitive and psychosocial profiles are shown in Fig. 3 (detailed information is provided in Table 1). Children with the slowest response times in Stroop and the lowest working memory score (i.e., DS, digital span) were in the EFD group (*p*s < 0.050 with Bonferroni's correction, same as below). For RAN, vocabulary, morphological awareness, and phonological awareness, children in

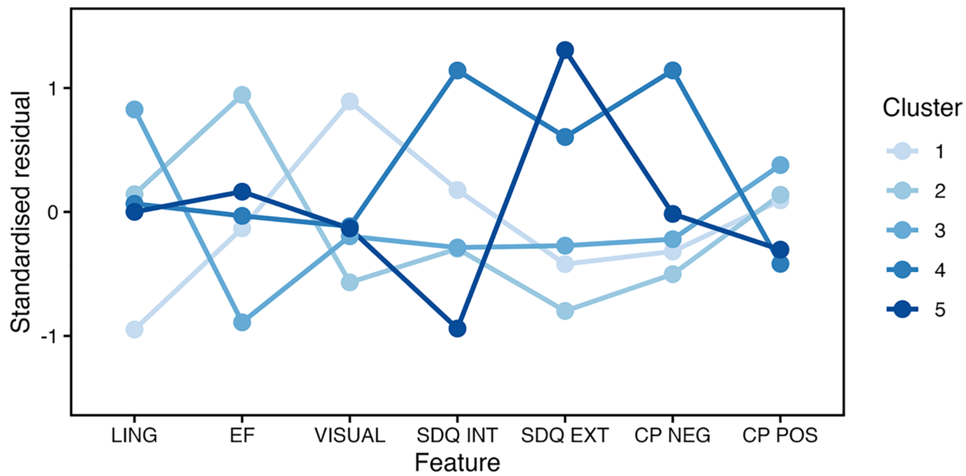

Fig. 1 Profile diagram of the seven features for each cluster. *Note*. LING = linguistic skills, EF = executive functioning, VISUAL = visual processing skills, SDQ INT = SDQ internalising problems, SDQ EXT = SDQ externalising problems, CP NEG = negative child-parent relationships, and CP POS = positive child-parent relationships

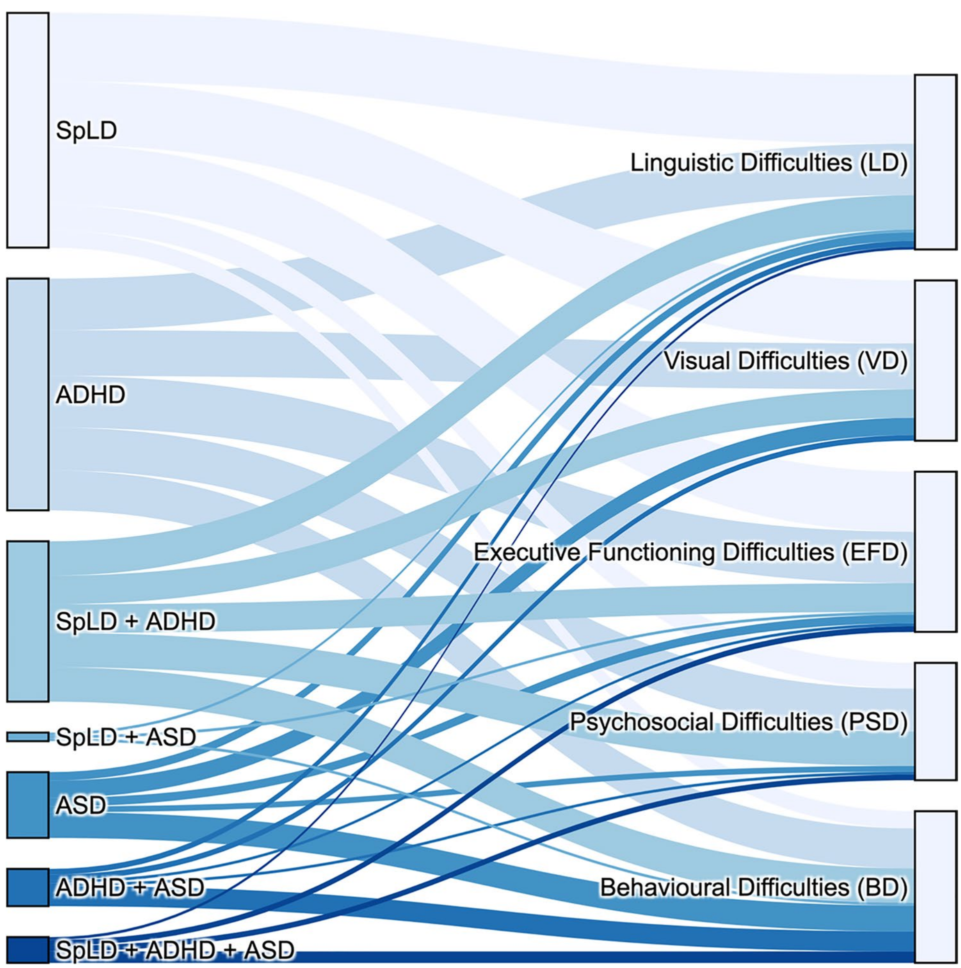

Fig. 2 Sankey diagram of the relationships between seven NDD types and five clusters

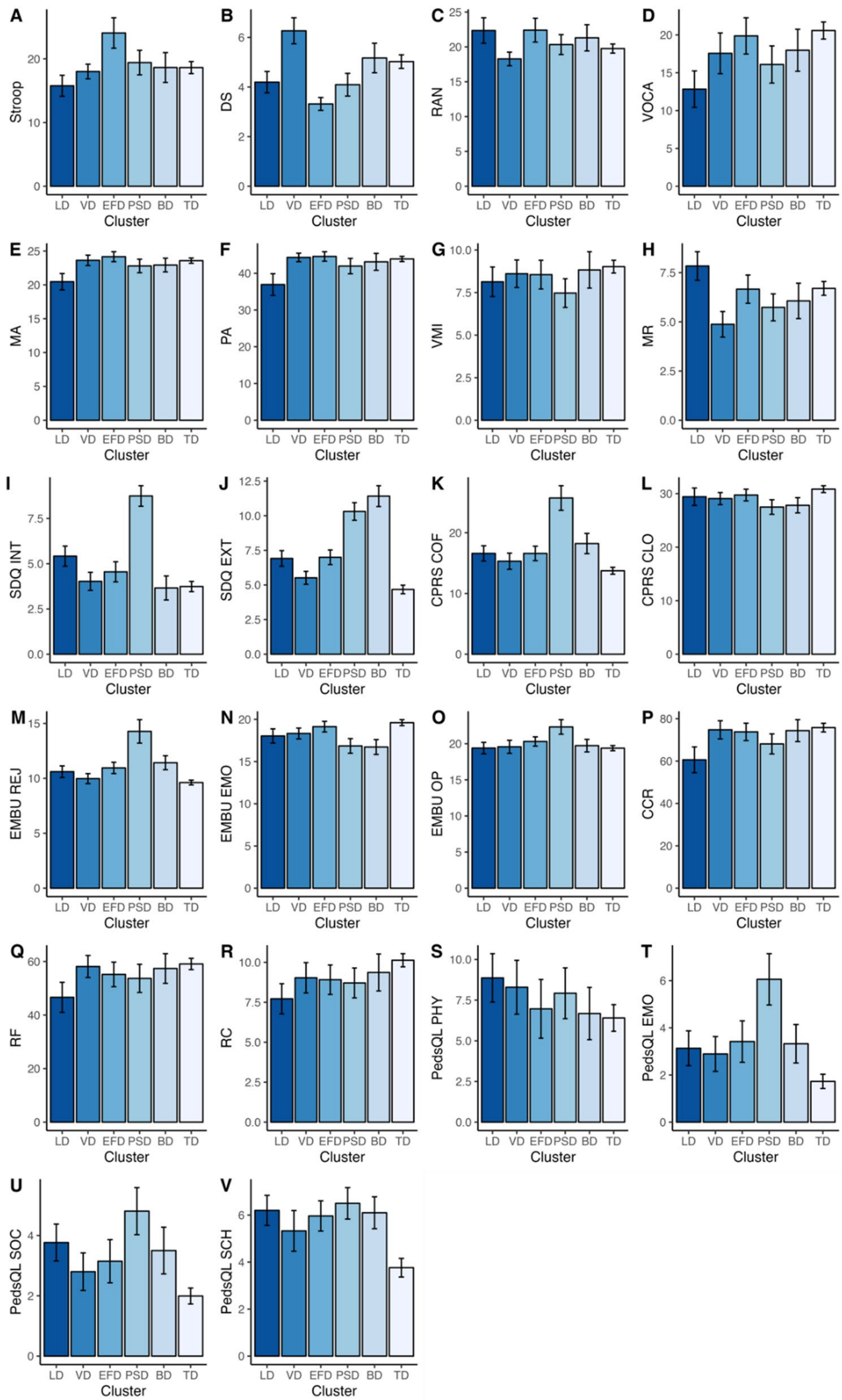

Fig. 3 Bar chart with error bars of group differences. *Note*. The error bars indicate 95% confidence intervals (CIs) of the means

Table 1 Descriptive statistics and group comparison results

Variable	Mean (SD)						Welch's ANOVA		Post-hoc comparison with Bonferroni's correction
	LD ($n=61$)	VD ($n=56$)	EFD ($n=56$)	PSD ($n=53$)	BD ($n=41$)	TD ($n=267$)	$F_{(5, 528)}$	η^2	
STROOP	15.78 (6.57)	18.02 (4.4)	24.07 (9.12)	19.42 (7.15)	18.64 (7.65)	18.64 (7.91)	6.48***	0.07	EFD > (VD, LD, PSD, BD, TD)
DS	4.20 (1.72)	6.27 (2.00)	3.32 (0.99)	4.09 (1.70)	5.17 (1.95)	5.03 (2.28)	28.37***	0.13	(EFD, LD, PSD, TD) < VD; EFD < (BD, TD); PSD < TD
RAN	22.35 (7.31)	18.27 (3.74)	22.4 (6.54)	20.33 (5.30)	21.30 (6.16)	19.76 (5.42)	5.56***	0.05	(EFD, LD) > (VD, TD)
VOCA	12.84 (9.59)	17.57 (10.28)	19.88 (9.15)	16.09 (9.12)	17.98 (9.07)	20.58 (9.38)	7.80***	0.07	LD < (EFD, TD); PSD < TD
MA	20.47 (4.82)	23.63 (2.95)	24.16 (2.80)	22.79 (3.71)	22.93 (3.31)	23.58 (3.24)	5.92***	0.08	LD < (VD, EFD, PSD, BD, TD)
PA	36.94 (11.74)	44.32 (4.39)	44.59 (4.89)	41.96 (7.78)	43.12 (7.53)	43.91 (5.90)	5.18***	0.10	LD < (VD, EFD, PSD, BD, TD)
VMI	8.13 (3.47)	8.61 (3.09)	8.55 (3.22)	7.47 (3.13)	8.83 (3.49)	9.02 (3.12)	2.52*	0.02	PSD < TD
MR	7.84 (2.89)	4.88 (2.48)	6.66 (2.74)	5.74 (2.54)	6.06 (2.94)	6.70 (2.92)	5.85***	0.07	VD < (EFD, LD, TD); (PSD, BD) < LD
SDQ INT	5.42 (2.21)	4.03 (1.91)	4.55 (2.12)	8.74 (2.11)	3.66 (2.16)	3.74 (2.36)	51.43***	0.31	PSD > LD > (VD, BD, TD); PSD > (EFD, LD, BD, TD)
SDQ EXT	6.92 (2.25)	5.52 (1.79)	7.00 (2.02)	10.31 (2.36)	11.42 (2.46)	4.68 (2.57)	89.99***	0.48	(PSD, BD) > (EFD, LD) > (VD, TD)
CPRS CONF	16.59 (5.02)	15.31 (5.08)	16.59 (4.55)	25.72 (7.53)	18.22 (5.44)	13.74 (4.76)	29.48***	0.32	PSD > (VD, EFD, LD, BD, TD); (EFD, LD, BD) > TD
CPRS CLOS	29.43 (6.48)	29.08 (4.33)	29.74 (4.17)	27.50 (5.06)	27.82 (4.63)	30.85 (5.33)	5.97***	0.05	(PSD, BD) < TD
EMBU REJ	10.61 (2.10)	9.98 (1.74)	10.95 (1.96)	14.28 (3.96)	11.42 (2.08)	9.62 (1.80)	21.38***	0.29	PSD > (EFD, LD, BD) > TD; (PSD, BD) > VD
EMBU EMO	18.03 (3.35)	18.33 (2.45)	19.14 (2.40)	16.86 (3.21)	16.72 (2.87)	19.61 (2.95)	13.20***	0.12	(VD, LD, PSD, BD) < TD; (PSD, BD) < EFD
EMBU OP	19.40 (3.15)	19.58 (3.44)	20.31 (2.44)	22.33 (3.73)	19.74 (2.84)	19.39 (2.95)	6.50***	0.08	PSD > (VD, EFD, LD, BD, TD)
CCR[a]	60.59 (24.27)	74.75 (16.32)	73.79 (15.68)	68.09 (17.57)	74.37 (16.90)	75.80 (17.15)	5.40***	0.07	LD < (VD, EFD, BD, TD)
RF[a]	46.62 (22.34)	58.13 (15.72)	55.18 (17.54)	53.70 (19.53)	57.39 (18.11)	59.08 (17.55)	3.80**	0.05	LD < (VD, TD)
RC[a]	7.72 (3.76)	9.03 (3.62)	8.91 (3.52)	8.71 (3.48)	9.37 (3.78)	10.13 (3.44)	5.47***	0.05	LD < TD
PedsQL PHY[a]	8.29 (6.32)	6.96 (6.89)	8.87 (5.94)	7.92 (5.80)	6.68 (5.25)	6.40 (6.84)	2.21	0.02	/
PedsQL EMO[a]	2.89 (2.82)	3.42 (3.35)	3.13 (2.94)	6.06 (4.04)	3.33 (2.66)	1.73 (2.52)	15.02***	0.17	PSD > (LD, VD, EFD, BD, TD); (VD, EFD, BD) > TD
PedsQL SOC[a]	2.80 (2.38)	3.15 (2.73)	3.77 (2.44)	4.81 (2.90)	3.50 (2.53)	1.99 (2.21)	14.03***	0.13	PSD > (LD, VD); (VD, EFD, PSD, BD) > TD
PedsQL SCH[a]	5.33 (3.31)	5.96 (2.46)	6.20 (2.55)	6.50 (2.49)	6.10 (2.22)	3.76 (3.30)	16.83***	0.13	(LD, VD, EFD, PSD, BD) > TD

Note. Visualised results can be found in Fig. 3. LD = Linguistic Difficulties; VD = Visual Difficulties; EFD = Executive Functioning Difficulties; PSD = Psychosocial Difficulties; BD = Behavioural Difficulties; TD = Typically Developing. STROOP = Stroop; DS = digit span; RAN = rapid naming; VOCA = vocabulary; MA = morphological awareness; PA = phonological awareness; VMI = visual-motor integration; MR = mental rotation; SDQ INT = SDQ internalising problems; SDQ EXT = SDQ externalising problems; CPRS CONF = CPRS conflict; CPRS CLOS = CPRS closeness; EMBU REJ, EMO, and OP = EMBU rejection, emotional warmth, and (over)protection; CCR = Chinese character reading; RF = reading fluency; RC = reading comprehension; PedsQL PHY, EMO, SOC, and SCH = PedsQL physical, emotional, social, and school functioning difficulties. For Welch's ANOVAs, * indicates $p < 0.05$, ** indicates $p < 0.01$, and *** indicates $p < 0.001$. In the last column, significant group differences are presented ($p < 0.05$ after Bonferroni's correction). For protective factors, the symbol > is used, and for risk factors, the symbol < is used, to place the group of interest for a specific protective/risk factor on the left for facilitating inspection. [a] indicates additional learning and mental health outcomes, which were not included during clustering

the LD group showed significant differences compared with TD and some other groups (ps < 0.050). For visual-motor integration, there was only a significant difference between the PSD group and the TD group ($p = 0.020$). For mental rotation, the VD group was significantly different from the TD children and the other two cognitive difficulties groups (ps < 0.050).

In terms of psychosocial factors, the PSD group showed the highest SDQ internalising problems score, and the PSD and BD groups showed SDQ externalising problems scores that were higher than the others (ps < 0.050). The two psychosocial difficulties groups also showed significantly higher CPRS conflict scores than the other groups and significantly lower CPRS closeness scores than the TD children (ps < 0.050). For EMBU rejection and emotional warmth, the two psychosocial difficulties groups were significantly different from the TD children and some of the other groups (ps < 0.050). For EMBU overprotection, the PSD group showed the highest score (ps < 0.050).

Learning and mental health profiles

Seven additional outcomes not included in the clustering were also compared (See Fig. 3; detailed information is provided in Table 1). The LD group showed worse Chinese character reading, reading fluency, and reading comprehension than some other cognitive difficulties groups and/or TD children (*p*s < 0.050). There were no significant results for PedsQL physical functioning difficulties (*p*s > 0.050). However, the PSD group showed more difficulties in emotional and social functioning than TD children and some other groups (*p*s < 0.050). All five groups also demonstrated more problems in schooling than the TD control (*p*s < 0.050).

Discussion

In the present study, we adopted a data-driven machine learning approach to explore the profiles of children with SpLD, ADHD, or ASD symptoms. Three cognitive factors and four psychosocial factors were first identified to reduce factor dimensions before clustering. As summarised in review papers, linguistic skills, EF, and visual processing have repeatedly emerged as three representative constructs for examining children's cognitive functions [82], including in Chinese children [83]. Similarly, the psychosocial constructs (e.g., internalising and externalising problems, plus positive/negative child-parent relationships) align with prior research [84, 85]. Therefore, the identified factors in the cognitive, psychological, and ecological domains were valid for putting into clustering analysis. Five clusters were revealed via k-means. The post-hoc comparisons confirmed the appropriateness of the symptom-based group labels.

The focus of the present study is to review the situation from the transdiagnostic and biopsychosocial perspectives. In our sample, over 30% of the children with NDD symptoms had more than one symptom. The comorbidity of SpLD and ADHD was about 35%, and of ASD and ADHD was about 44.7%. These findings supported our earlier argument that there were high rates of overlap in NDD symptoms [13], emphasising the need for a transdiagnostic approach to uncover shared mechanisms across them. On the other hand, whereas the literature mostly focused on cognitive impairments, our findings on the roles of psychosocial factors support the application of a biopsychosocial model in NDD research. Some researchers may argue that introducing psychosocial factors into (trans)diagnostic models may obscure the essential neurocognitive/behavioural mechanisms, as NDDs were traditionally defined by (neuro)cognitive developmental deficits. This critique holds merit from a conventional view of psychopathological diagnosis. On the other hand, the World Health Organization (WHO) (2007, p. 19) states that the goal of classification is "not a diagnosis for a child, but a profile of its functioning". Although probably not the initial base of NDDs, psychosocial factors should still be considered, as a growing body of research has shown that these factors can moderate how functioning difficulties manifest and impact children's daily lives [86–89].

Heterogeneity, commonalities, and continuum are representative concepts that illustrate the complexity of NDDs. By combining the transdiagnostic and biopsychosocial approaches, our data-driven clustering findings provide an empirical demonstration of *heterogeneity* within traditional diagnostic categories (e.g., children with SpLD-only can be divided into three different cognitive-deficit groups) and *commonalities* across them (e.g., the EFD group includes children with symptoms of either SpLD, ADHD, or ASD only). We also find that the LD group and the PSD group exhibited more severe symptoms and worse scores in learning or well-being measures than others, supporting the assumption of the *continuum* of the development of NDDs, instead of a simple dichotomy of diagnosed or non-diagnosed. These findings can serve as a channel for reviewing and reflecting on both the theoretical framework and practice mechanisms of understanding and supporting children with different patterns in NDD symptoms. Transdiagnostic and biopsychosocial approaches are needed but should not be viewed as mere replications or challenges to conventional diagnostic standards; instead, they provide a complementary framework to advance the understanding of NDD commonalities, refine the purpose of diagnosis, inform inclusive education research and practice, and move the field forward.

Some specific findings are discussed as follows. Based on the identified five-cluster solution, the LD group emerged as a severe cognitive deficits group (i.e., worse VOCA, MA, and PA) and was also related to worse CCR, RF, and RC when comparing learning outcomes. These findings were not surprising as these cognitive deficits have been proven to predict reading in Chinese [90, 91]. Furthermore, 26.23% of children in this group had more than one NDD symptom. According to a systematic review, a large number of Chinese reading difficulties studies from the 1960s to 2015 primarily assessed reading difficulties while excluding other NDD types or did not provide screening information for comorbidity [92]. This limitation has recently garnered more attention; for example, the shared cognitive predictors of ADHD and reading difficulties were widely reported in the Chinese population [14, 93, 94]. Currently, linguistic intervention programmes are commonly provided for children with dyslexia/language disorders [95, 96], but scant studies targeted training in the linguistic skills of children with ADHD or ASD (e.g., see a review by [95–97]), probably because linguistic problems were not believed to be the most critical of them. Such a framework may result in missed opportunities to develop a comprehensive support strategy. Instead, our findings show the promise of focusing on children's common linguistic difficulties, regardless of the specific NDD label(s) they have. Future intervention studies may follow this approach and develop a symptom-focused screening process rather than one based on diagnostic labels, which can lead to the exclusion of children with "irrelevant" diagnoses, though they may also benefit from the intervention.

EF and visual deficits have been reported in a variety of NDDs [98, 99]. In our sample, we concluded that the EFD and VD groups were mild-symptom groups, as they exhibited less severe and less diverse cognitive deficits compared to the LD group. Nevertheless, the sources of these three cognitive groups were similar, and EF and visual deficits in a variety of NDDs have been reported [98–102], thereby showing the significance of the transdiagnostic method and the need for symptom-targeted intervention. The cognitive measures were intercorrelated (see Supplementary Fig. 2), and the literature suggests that basic cognitive skills can impact literacy outcomes indirectly through linguistic skills [103–105], so it is still possible that these executive and visual processing problems (e.g., fail to recognise words) can develop into severe linguistic/learning processing difficulties if immediate external support is lack. In the theoretical regard, a relatively worse condition in the LD group can be explained as the manifestation of multiple deficits [106], while children in the EFD or VD group can use linguistic skills to compensate for basic cognitive skills to perform well in academics [107]. More research is warranted to uncover the mechanism of the cognitive profile of NDD children.

The PSD group seemed to be the most severe in the psychosocial domain and mental health outcomes. Children in this group showed extremely high scores in internalising and externalising problems, CPRS conflict, and EMBU rejection in our sample, indicating relatively severe individual problems and a negative family environment. They also showed significant differences in CPRS closeness, EMBU emotional warmth, and overprotection compared with the TD control and/or some other clusters. Recent studies have documented the comorbidity of SpLD, ADHD, or ASD with psychological issues (e.g., anxiety, depression, behavioural problems) and child-parent relationships (e.g., [108]). These factors can either exacerbate or mitigate NDD symptoms [109–111]. In this regard, strategies that target children's emotional regulation or parenting (e.g., mindfulness-based interventions) [112–114] should be adopted to support the psychological resilience of children with NDDs. Meanwhile, children in the BD group mainly demonstrated externalising problems (e.g., conduct problems and hyperactivity). While these are the core features of ADHD, the condition frequently co-occurs with other NDDs. This high rate of comorbidity could explain why 45.28% of the children in the BD group exhibited characteristics associated with more than one NDD condition. In this case, interventions focusing on externalising problems may help.

Some limitations should be mentioned. First, the less acceptable internal reliability for some measures (e.g., MA and SDQ) could underestimate the effects. In the original study that adopted internalising and externalising composite scores of SDQ, researchers reported relatively lower reliability in parent- ($\alpha = 0.66–0.78$) and youth-reported results ($\alpha = 0.66–0.76$), while the reliability of teachers' reports was better in the UK sample ($\alpha = 0.80–0.88$). In addition, we only examined a typical task (i.e., homograph awareness) of MA due to time constraints, while the other two aspects (i.e., homophone awareness and compounding structure awareness) were not included [115]. Future studies should re our findings using more comprehensive cognitive measures and a multi-informant method for psychosocial variables. Second, the silhouette scores, gap statistics, and the ARI were not exceptionally good in our sample. This is reasonable because the transdiagnostic pattern is typically "fuzzy" [7]. Instead of searching for a "gold" standard of clustering, our purpose is to use exploratory empirical findings to provide insight into the complexity of NDDs (i.e., heterogeneity, commonalities, and continuum) [25], which has not been fully covered by the existing system. Modelling high-dimensional constructs can be challenging. Future studies should employ other advanced machine learning algorithms tailored to complex transdiagnostic data to further confirm the pattern. Third, although we adopted the ARI for internal reproducibility evaluation in clustering, these results still lack external validation. Future studies should validate the significance of a transdiagnostic-biopsychosocial model using clinically meaningful data, such as neuroimaging markers and treatment responses, to investigate whether the model truly aids in screening/intervention.

Despite these limitations, to the best of our knowledge, this study is among the first to profile children with NDD symptoms based on both transdiagnostic and biopsychosocial perspectives. In traditional diagnostic systems, many children present with multiple NDD symptoms yet obtain only a single diagnosis, or none at all, if their symptoms fall below diagnostic thresholds. We do not aim to replace these systems, as they are essential in various ways (e.g., prescribing medication). However, one noticeable issue is that NDDs "… are very few pure subtypes. This means that some children are left in what is an uncertain area in that no particular category will reflect a very general picture of their needs" ([116], p. 209). A key contribution of the transdiagnostic approach is rectifying this limitation, ensuring that children with significant NDD symptoms but neglected by the existing diagnostic systems receive the adequate attention and support they need. As evidence, our findings underscore the need to provide comprehensive support for children by addressing their weaknesses across multiple domains. We must prioritise the continuum of symptom severity across NDDs, which means responding to all manifestations of children's challenges with an inclusive, non-binary perspective in favour of recognising diversity and individuality. Such an ethos of maximal inclusivity and support aligns with the foundational principles of inclusive education.

As Carl Sagan noted, "It is far better to grasp the universe as it really is than to persist in delusion, however satisfying and reassuring". Referring to this philosophy, our transdiagnostic, biopsychosocial profiles move beyond the conventional diagnostic labels to grasp the complex reality of children's needs. In addition to its theoretical significance, the identified clustering profiles provide a practical framework for designing and delivering support more effectively. Clinically, they call for a shift from diagnosis-driven to profile-driven intervention. For example, we may prioritise literacy training for the LD group regardless of diagnosis, provide proactive accommodations for the VD and EFD groups before academic failure occurs, and integrate mental health and family support for the PSD and BD groups. In educational systems, these profiles can inform the development of a more precise school-based screening system to identify at-risk children earlier and allocate resources, such as learning accommodation strategies and support from specific teaching staff, based on the personalised profiles of the children rather than diagnostic counts. To some extent, this could be treated as an upgraded version of the implemented Response-to-Intervention (RTI) method for supporting children with SEN, which is applied in Hong Kong [117], and shows potential to apply to a wider area in other regions of China, where individual heterogeneity could be more diverse across regions. One direction of future research could be to develop and test cluster-specific interventions to establish evidence-based, personalised pathways from assessment to support. By focusing on functional profiles rather than categorical labels, we take a concrete step toward an educational and clinical practice to support every child, bearing the authentic nature of inclusion.

Supplementary Information

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Supplementary Material 1

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Author contributions
LD contributed to the research design, data acquisition, analysis, and manuscript drafting and review. WZ contributed to data analysis, manuscript drafting, and review. LL was responsible for data collection and curation, and led the initial stages of formal data analysis. All other co-authors contributed to the conceptualisation, measurement preparation, and manuscript revision. XG also provided guidance on data analysis. All authors read and approved the final manuscript.

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Data availability
The datasets used and analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Informed consent has been obtained from the school and parents. This study was approved by the Human Research Ethics Committee (HREC) of The Education University of Hong Kong (Date of approval: 30th June 2022; Ref. no. 2021-2022-0332) and conformed to the Declaration of Helsinki.

Consent for publication
Not applicable. This study does not contain any individual's data in any form.

Competing interests
The authors declare no competing interests.

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