Research Square

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Trajectory of Refractive Change and Its Influencing Factors in Preschool Children: A Longitudinal Study

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Abstract

Background

Early-onset myopia increases the risk of high myopia in adolescence. This study aimed to identify heterogeneous trajectories of refractive change in preschool children using the Latent Growth Mixture Model (LGMM) and to explore their associated influencing factors, thereby providing a scientific basis for precise myopia prevention and control.

Methods

Cluster sampling was used to recruit 956 preschool children from 27 kindergartens in Haidian District, Beijing, between October 2021 and October 2023. A basic information questionnaire was administered to collect general demographic data. Ocular refractive biometry was performed annually to track the changes in refractive status over the 2-year follow-up period. LGMM was used to identify heterogeneous refractive trajectories. Multinomial logistic regression analysis was subsequently used to explore the factors associated with trajectory membership.

Results

Three distinct refractive change trajectories were identified: the slow change group (*n* = 111, 11.6%), the stable change group (*n* = 714, 74.7%), and the rapid change group (*n* = 131, 13.7%). Multinomial logistic regression revealed that children's age, sex, parental moderate-to-high myopia, and daily outdoor activity duration were independent predictors of latent classes for refractive development trajectories in preschool children.

Conclusions

Preschool children exhibit three distinct trajectories of refractive change, demonstrating significant population heterogeneity. Myopia prevention strategies may benefit from risk stratification based on early refractive trajectories.

Background

Myopia has evolved into a severe global public health concern. It is projected that 49.8% of the global population (4.76 billion individuals) will develop myopia by 2050, with 9.8% progressing to high myopia [1, 2]. As the world's most populous country, China suffers from a high prevalence of myopia accompanied by a striking younger-onset trend. According to surveillance data released by the National Health Commission of China, the overall myopia prevalence among Chinese children and adolescents reached 52.7% in 2020, while the prevalence among 6-year-old children stood at 14.3% [3]. Existing evidence indicates that younger age and higher baseline refractive error are associated with a greater risk of myopia progression [4]. Preschool children (under 7 years old) are in a critical period of ocular and visual development, rendering them highly vulnerable to environmental risk factors. Furthermore, an earlier onset of myopia prolongs the progressive course and increases the likelihood of high myopia in adulthood [5, 6]. High myopia further elevates the risk of irreversible visual impairment and even blindness due to complications such as retinal detachment and myopic maculopathy [7, 8]. The 2025 Chinese Expert Consensus on Pre-myopia Management has identified preschool children as a core population for myopia monitoring and intervention, highlighting the necessity of shifting the focus of childhood myopia prevention and control forward to the preschool stage [9].

A multicenter survey across multiple Chinese provinces reported a 5.5% myopia prevalence among preschool children [10]. By comparison, the corresponding prevalence rates in Japan are 2.9% for overall myopia and 0.2% for high myopia in the same age group. For children aged 4 to 6 years, axial length, age, sex and parental myopia have been confirmed as key predictors of myopia development [11]. Refractive status changes substantially with age during early childhood. Previous studies have documented the mean right-eye spherical equivalent (SE) as 1.31 ± 0.84 D, 1.30 ± 0.76 D, 1.17 ± 0.84 D, and 1.06 ± 0.80 D among preschool children aged 3, 4, 5 and 6 years, respectively [12]. Additionally, numerous studies have linked myopia onset to daily behavioral patterns, including outdoor activity duration, prolonged screen time, and sleep length [13, 14]. However, most existing investigations adopt a cross-sectional design. Although such studies are effective for estimating prevalence and identifying correlational factors, they fail to capture dynamic changes in refractive status over time. Methodologically, cross-sectional designs are inherently limited in analyzing time-series dynamics [15]. Conventional uniform analytical approaches obscure individual heterogeneity in developmental trajectories; averaging across populations conceals subgroup differences and impedes personalized prognosis based on baseline characteristics. Longitudinal data are therefore essential for clarifying disease progression and determining optimal intervention windows. Prospectively designed cohort studies overcome these limitations by collecting repeated measurements to characterize developmental trajectories [15].

To address the above limitations and move beyond population-level overall trends, the present study adopted a prospective longitudinal design. We conducted a 2-year follow-up among children aged 3–6 years recruited from 27 kindergartens in Haidian District, Beijing. Latent Growth Mixture Modeling (LGMM) was applied to construct refractive developmental trajectories. We further explored the effects of ocular biometric parameters, birth history, lifestyle and environmental factors, as well as familial factors on heterogeneous refractive trajectory subgroups. The findings aim to provide empirical evidence for establishing a trajectory-based precise risk prediction model for preschool myopia, and to support the development of individualized early intervention strategies. This study ultimately seeks to advance the timing of childhood myopia prevention and control in clinical practice.

Methods

Ethics approval

This study was conducted in accordance with the tenetsof the Declaration of Helsinki and received approval from the Ethics Committee of Beijing Tongren Hospital, Capital Medical University (Approval Number: TRECK-Y2019-152). Before inclusion in the study, all participants provided informed consent.

Study design and population

This study was conducted from October 2021 to October 2023. Cluster sampling was used to recruit 1,878 children aged 3-6 years from 27 kindergartens in Haidian District, Beijing. The sample size was determined to meet the analytical requirements of LGMM, for which a minimum sample of 200 participants is recommended [16].

The inclusion criteria were as follows: children aged 3-6 years; ability to cooperate with ophthalmic examinations; and provision of written informed consent by legal guardians following voluntary participation agreement. The exclusion criteria included: a history of contraindications or adverse reactions related to cycloplegia; presence of other ocular diseases such as strabismus, amblyopia, cataract, glaucoma, and retinal disorders; and loss to follow-up resulting from myopia control interventions (e.g., orthokeratology lenses, atropine eye drops), school transfer, or other reasons.

Follow-up

This study adopted a longitudinal observational design. Ocular refractive and biometric parameters, including spherical equivalent (SE), axial length (AL), and mean corneal curvature (CR), were measured annually throughout follow-up. A standardized questionnaire was administered to collect children's demographic information and parental myopia status. Due to disruptions related to the COVID-19 pandemic and other unforeseen factors, 966 children completed the two-year follow-up assessments. After excluding 10 invalid data records, a final sample of 956 participants was included in the statistical analysis.

Outcome measures

Basic information questionnaire

The research team developed a structured questionnaire based on a comprehensive literature review and expert consultation to collect participants' baseline characteristics. The questionnaire covered demographic information (sex, age, height, weight), perinatal factors (birth weight and gestational age), lifestyle factors (daily outdoor activity duration and dietary habits), and parental myopia status.

Measurement of refractive and ocular biometric parameters

Cycloplegic refraction

Refractive measurements were performed before and after cycloplegia using an KR-8900 autorefractometer (Topcon Corporation, Tokyo, Japan). Cycloplegia was induced with 1.0% cyclopentolate hydrochloride eye drops, administered three times at intervals of 5 to 10 minutes. One hour after the first instillation, pupillary response and dilation were evaluated. Complete cycloplegia was defined as an absence of pupillary light reflex and a pupil diameter greater than 6.0 mm. If adequate cycloplegia was not achieved, an additional drop of 1.0% cyclopentolate hydrochloride was administered. Persistent failure to meet the pupillary criteria within 15 minutes after supplementation was recorded as unsuccessful cycloplegia. During examinations, participants were positioned with their chin on the chin rest and forehead against the head support to stabilize the head. All children were instructed to fixate on the internal target of the autorefractometer. Three consecutive readings of spherical power, cylindrical power, and astigmatic axis were obtained for each eye, and the average values were calculated for subsequent analysis.

Ocular biometry

Ocular biometric parameters were measured using the IOL Master (Carl Zeiss Meditec AG, Jena, Germany), a non-contact optical biometer. The measured parameters included axial length (AL), horizontal corneal power (K1), and vertical corneal power (K2).The average corneal power (K) was calculated as the mean of K1 and K2. The corneal curvature radius (CR) was derived using the formula:

$$CR = 1000 \times (n_2 - n_1) / K$$

where n_1 is the refractive index of air (1.0000) and n_2 is the refractive index of the cornea (1.3375). The AL/CR ratio was subsequently calculated based on the measured AL and derived CR.Myopia was defined as a SE refractive error of ≤−0.50D [17].

Data collection and quality control

The research team consisted of three ophthalmologists, five ophthalmic technicians, three head nurses, and two postgraduate students. All team members signed confidentiality agreements and completed standardized training prior to the study initiation. The training covered data security protocols, participant privacy protection, and ethical management of protected health information (PHI). Access to study data was strictly restricted to authorized researchers, who were only permitted to access data relevant to their designated research responsibilities.

Data collection

Questionnaire data

General information was collected using an electronic questionnaire, which was distributed to and completed by the children's parents or primary caregivers. Upon clicking "submit" after completion, the questionnaires were automatically uploaded to a dedicated online data collection platform.

Refractive and biometric data

A standardized examination form was assigned to each child before every assessment. All refractive and ocular biometric measurements were recorded immediately by trained technicians upon completion of testing. After a participant finished all examinations, research staff collected the forms and performed an initial review to verify data completeness. All valid records were subsequently extracted and imported into a centralized electronic database for unified management and collation.

Quality control

Training and calibration

All study personnel completed unified training on the study protocol and standardized operating procedures for all ophthalmic examinations prior to data collection initiation. Before each measurement session, all ophthalmic instruments were calibrated and maintained to ensure the accuracy and reliability of the measurement results.

Intra-day quality assessment

To monitor measurement consistency, 5% of the participants examined each day were randomly selected for retesting. The acceptable measurement error for SE was set at ±0.50D, and AL≤0.1 mm. If the daily error rate exceeded 5%, the underlying causes were promptly analyzed, and corrective actions were implemented to improve measurement quality.

Data entry and cleaning

Data were independently entered by two trained researchers and subsequently cross-validated to identify discrepancies. Only records with confirmed agreement were included in the statistical analyses. Participants with more than 20% missing data across variables were excluded from the final analysis.

Statistical analysis

All statistical analyses were performed using SPSS version 26.0 (IBM Corp., Armonk, NY, USA). Continuous variables following a normal distribution are presented as mean ± standard deviation (SD) and were compared using one-way analysis of variance (ANOVA). Categorical variables are summarized as frequencies and percentages, with group differences assessed using the chi-square test or Fisher's exact test, as appropriate. Ordinal variables were analyzed using the rank-sum test. Multivariable logistic regression was conducted to identify potential factors associated with refractive outcomes.

LGMM was conducted using Mplus version 8.0 (Muthén & Muthén, Los Angeles, CA, USA) following a two-step procedure. First, to evaluate potential heterogeneity in children's refractive change trajectories, a series of LGMMs with increasing numbers of latent classes were fitted. Model fit was assessed using multiple criteria, including the Akaike Information Criterion (AIC), Bayesian Information Criterion (BIC), and sample-size adjusted BIC (aBIC), with lower values indicating better fit. Classification quality was evaluated using entropy, with higher values indicating improved classification accuracy. Model comparisons were further supported by the Lo–Mendell–Rubin likelihood ratio test (LMR-LRT) and the bootstrapped likelihood ratio test (BLRT), with statistically significant P values indicating improved model fit relative to models with fewer classes [18]. The optimal number of latent trajectory classes was determined based on a comprehensive evaluation of model fit indices, classification performance, statistical significance, and interpretability.

Second, after identifying the optimal trajectory classes, multinomial logistic regression was performed to examine associations between demographic characteristics and trajectory class membership. To evaluate the robustness of the findings, a sensitivity analysis was conducted by additionally adjusting for baseline axial length in the multinomial logistic regression model.

Results

Baseline characteristics and myopia prevalence at each follow-up wave

A total of 1,864 children aged 3-6 years were enrolled at baseline. The mean SE refractive error was 1.15 ± 0.94 D, and the overall prevalence of myopia was 4.61% (86/1,864). The prevalence was 5.35% (52/972) in boys and 3.81% (34/892) in girls, with no significant sex difference (P = 0.158). At the 1-year follow-up, 1,508 children completed the examination, with an overall myopia prevalence of 3.65% (55/1,508), including 3.40% (27/795) in boys and 3.93% (28/713) in girls. At the 2-year follow-up, 956 children (489 boys and 467 girls) completed the examinations. The overall myopia prevalence was 7.85% (75/956), including 8.79% (43/489) in boys and 6.85% (32/467) in girls. The sex difference remained non-significant (P = 0.36).

Identification and determination of latent classes of refractive change trajectories in preschool children

LGMM was performed to identify heterogeneous trajectories of refractive change by fitting models with 1 to 5 latent classes. The Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) decreased progressively with increasing numbers of classes. Entropy values exceeded 0.80 for all models with 2-5 classes, indicating good classification quality. Among the candidate models, only the 3-class solution yielded statistically significant results for both the Vuong–Lo–Mendell–Rubin likelihood ratio test (VLMR-LRT) and the bootstrapped likelihood ratio test (BLRT) ($P < 0.05$), suggesting improved model fit compared with models with fewer classes. In addition, the 3-class model demonstrated an adequate class distribution, with the smallest class

comprising more than 10% of the total sample and including over 50 participants. Based on overall model fit, classification performance, and clinical interpretability, the 3-class model was selected as the optimal solution (Table 1).

Table 1 Model fit indices for latent class growth models of refractive change trajectories in preschool children

Class	AIC	BIC	aBIC	Entropy	VLMRT	BLRT	Class probabilities				
							1	2	3	4	5
1	7006.651	7030.965	7015.085	-	-	-	1.000	-	-	-	-
2	6274.605	6313.507	6288.099	0.833	0.183	□0.001	0.837	0.163	-	-	-
3	5560.523	5614.013	5579.078	0.887	0.040	□0.001	0.137	0.116	0.747	-	-
4	5089.315	5157.393	5112.930	0.863	0.118	□0.001	0.032	0.569	0.315	0.084	-
5	4795.329	4877.996	4824.005	0.860	0.097	□0.001	0.060	0.020	0.355	0.117	0.448

Abbreviations: AIC, Akaike Information Criterion; BIC, Bayesian Information Criterion; aBIC, sample-size adjusted BIC; VLMR T, Vuong-Lo-Mendell-Rubin test; BLRT, Bootstrapped Likelihood Ratio Test.

Nomenclature of latent classes of refractive change trajectories

Based on the optimal 3-class model, a latent class trajectory plot was generated with time points as the x-axis and SE refractive error at three measurement time points as the y-axis (Figure 1). The three latent classes were named according to the rate of refractive change: the slow refractive change group (*n*=111, 11.6%), the stable refractive change group (*n*=714, 74.7%), and the rapid refractive change group (*n*=131, 13.7%). Detailed parameter estimates for the 3-class model are presented in Table 2.

Table 2 Parameter estimates of the 3-class LGMM for refractive change trajectories

Class	Parameter	Estimate	Standard error	*P-value*
Slow change group	Mean baseline SE	-0.013	0.155	0.932
	Mean SE change rate	-0.164	0.072	□0.001
	Variance of baseline SE	0	0	-
	Variance of SE change rate	0	0	-
Stable change group	Mean baseline SE	1.149	0.062	□0.001
	Mean SE change rate	-0.172	0.009	□0.001
	Variance of baseline SE	0	0	-
	Variance of SE change rate	0	0	-
Rapid change group	Mean baseline SE	2.282	0.164	□0.001
	Mean SE change rate	-0.372	0.024	□0.001
	Variance of baseline SE	0	0	-
	Variance of SE change rate	0	0	-

Univariate analysis of latent classes of refractive change trajectories in preschool children

Univariate analyses showed no significant differences among trajectory classes with respect to gestational age, birth weight, baseline body BMI, picky eating behavior, or preference for sweet foods (all $P > 0.05$). Variables demonstrating statistically significant differences across trajectory classes are presented in Table 3.

Multivariate analysis of latent classes of refractive change trajectories in preschool children

Multinomial logistic regression was performed to examine factors associated with trajectory class membership, with the slow refractive change group specified as the reference category. Variables that were statistically significant in the univariate analysis were included as independent variables.

Compared with the slow change group, older age was associated with a lower likelihood of belonging to the stable change group (*OR* = 0.683, $P = 0.001$). Paternal myopia with SE < −3.00 D was associated with reduced odds of membership in the stable change group (*OR* = 0.512, $P = 0.019$), and maternal myopia with SE < −3.00 D showed a similar association (*OR* = 0.350, $P = 0.002$). Relative to the slow change group, older age was also associated with a lower likelihood of belonging to the rapid change group (*OR* = 0.615, $P = 0.001$). Paternal myopia with SE < −3.00 D was associated with substantially lower odds of membership in the rapid change group (*OR* = 0.182, $P < 0.001$), and maternal myopia with SE < −3.00 D was likewise associated with reduced odds (*OR* = 0.252, $P = 0.001$).

A sensitivity analysis was conducted with baseline axial length (AL) additionally included as a covariate. After adjustment for AL, paternal myopia with SE < −3.00 D was associated with an increased likelihood of belonging to the rapid refractive change group (*OR* = 2.21, 95% *CI*: 1.28–3.83, *P* = 0.005), and maternal myopia with SE < −3.00 D showed a similar association (*OR* = 2.42, 95% *CI*: 1.31–4.47, *P* = 0.005). Furthermore, each 1-mm increase in baseline AL was associated with a 2.57-fold increase in the odds of membership in the rapid change group (*OR* = 2.57, 95% *CI*: 1.91–3.46, *P* < 0.001) (Table 4).

Table 3 Univariate analysis of latent classes of refractive change trajectories in preschool children (*n*= 956)

Variables	Total(n=956)	Slow change group(n=111)	Stable change group(n=714)	Rapid change group(n=131)	X^2/H
Baseline age (years)	4.00 [3.00, 5.00]	4.00 [4.00, 5.00]	4.00 [3.00, 4.00]	4.00 [3.00, 4.50]	11.149
Birth weight (kg)	3.35[3.03,3.65]	3.30 [3.04, 3.50]	3.35 [3.02, 3.70]	3.36 [3.10, 3.67]	1.651
Gender (%)					6.518
Male	496 (51.9)	63 (56.8)	378 (52.9)	55 (42.0)	
Female	460 (48.1)	48 (43.2)	336 (47.1)	76 (58.0)	
Gestational age (weeks) (%)					2.725
28-37	133 (13.9)	19 (17.1)	101 (14.1)	13 (9.9)	
37-40	823 (86.1)	92 (82.9)	613 (85.9)	118 (90.1)	
Paternal diopter (%)					41.824
−0.50 D≥SE ≥ −3.00 D	270 (28.2)	25 (22.5)	212 (29.7)	33 (25.2)	
SE≤-3.00D	419 (43.8)	68 (61.3)	315 (44.1)	36 (27.5)	
SE≥-0.50D	267 (27.9)	18 (16.2)	187 (26.2)	62 (47.3)	
Maternal diopter (%)					21.766
−0.50 D≥SE ≥ −3.00 D	250 (26.2)	22 (19.8)	186 (26.1)	42 (32.1)	
SE≤-3.00D	508 (53.1)	78 (70.3)	376 (52.7)	54 (41.2)	
SE≥-0.50D	198 (20.7)	11 (9.9)	152 (21.3)	35 (26.7)	
Baseline BMI (kg/m²) (%)					6.884
Overweight/Obesity	25 (2.6)	1 (0.9)	20 (2.8)	4 (3.1)	
Underweight	96 (10.0)	17 (15.3)	71 (9.9)	8 (6.1)	
Normal weight	835 (87.3)	93 (83.8)	623 (87.3)	119 (90.8)	
Daily outdoor activity (h) (%)					3.775
≤2	479 (50.1)	62 (55.9)	360 (50.4)	57 (43.5)	
≥2	477 (49.9)	49 (44.1)	354 (49.6)	74 (56.5)	
Picky eating (%)					1.384
Never	184 (19.2)	25 (22.5)	133 (18.6)	26 (19.8)	
Frequently	173 (18.1)	21 (18.9)	127 (17.8)	25 (19.1)	
Occasionally	599 (62.7)	65 (58.6)	454 (63.6)	80 (61.1)	
Preference for sweet foods (%)					5.001
Never	25 (2.6)	6 (5.4)	17 (2.4)	2 (1.5)	
Frequently	448 (46.9)	55 (49.5)	332 (46.5)	61 (46.6)	
Occasionally	483 (50.5)	50 (45.0)	365 (51.1)	68 (51.9)	

Table 4 Multinomial logistic regression analysis of latent classes of refractive change trajectories in preschool children

Variables	Stable change group (vs. slow change group)			Rapid change group (vs. slow change group)		
	β(SE)	P-value	OR(95 %CI)	β(SE)	P-value	OR(95 %CI)
Baseline age (years)	-0.381(0.115)	0.001	0.68(0.55~0.86)	-0.486(0.152)	0.001	0.62(0.46 ~0.83)
Gender	0.286(0.212)	0.177	1.33(0.88~2.01)	0.792(0.272)	0.004	2.21(1.30 ~3.76)
Paternal diopter (SE≤-3.00D)	-0.670(0.286)	0.019	0.51(0.29~0.90)	-1.705(0.346)	<0.001	0.18(0.09 ~0.36)
Maternal diopter (SE≤-3.00D)	-1.050(0.342)	0.002	0.35(0.18~0.68)	-1.377(0.401)	0.001	0.25(0.12 ~0.55)
Daily outdoor activity (h)	0.284≤0.218≤	0.013	0.12(0.11~0.76)	0.312≤0.276≤	<0.001	0.17≤0.03 ~0.26≤
Baseline axial length (AL, per 1 mm increase)	—	—	—	0.943(0.152)	<0.001	2.57(1.91 ~3.46)

Note: AL was only included in the rapid change group model for sensitivity analysis; OR for AL was calculated per 1 mm increment.

Discussion

Heterogeneous latent classes of refractive change trajectories in preschool children

This study applied LGMM to characterize 2-year longitudinal trajectories of refractive development among preschool children in Haidian District, Beijing. Moving beyond the assumption of homogeneous developmental patterns inherent in conventional growth models, three distinct latent trajectory classes were identified: the slow refractive change group, stable refractive change group, and rapid refractive change group. The distribution of these classes was balanced (11.6%, 74.7%, and 13.7%, respectively), and model fit indices indicated good classification performance (entropy = 0.887; both the Vuong–Lo–Mendell–Rubin likelihood ratio test [VLMR-LRT] and the bootstrapped likelihood ratio test [BLRT] $P < 0.05$). These findings highlight substantial heterogeneity in refractive development during the preschool period and provide a useful framework for understanding early-life variation in refractive trajectories and identifying children at elevated risk of myopia.

Stable refractive change group: the largest category of refractive development

In this study, 74.7% of preschool children were classified into the stable refractive change group, characterized by mean SE values of 1.106 D, 1.053 D, and 0.750 D at T1, T2, and T3, respectively, demonstrating a gradual decline over time (slope = −0.172, $P < 0.001$). This trajectory is consistent with the physiological process of emmetropization observed during early childhood. Most children are born with mild hyperopia, which gradually decreases as ocular structures develop, including axial elongation and coordinated adjustment of corneal and lens refractive power. The modest reduction in SE observed in this group likely reflects normal maturation of the refractive system and appropriate coupling between ocular growth and optical power [19]. Children in this trajectory class exhibited a refractive development pattern indicative of relatively balanced ocular growth, which may correspond to a lower probability of early myopia onset. Previous longitudinal studies have similarly reported relatively stable refractive changes during the preschool years [20–21]. For example, Yu et al. [22] conducted a 3-year cohort study in Shanghai and found that refractive changes occurred more gradually among children aged 3-6 years than among those aged 7-9 years, supporting the view that refractive development during early childhood generally follows a regulated physiological course.

Rapid refractive change group: a high-risk population requiring early intervention

Approximately 13.7% of children were classified into the rapid refractive change group. Although this group exhibited the highest baseline SE value (T1 = 2.247 D), it showed the steepest decline over time (slope = −0.372, $P < 0.001$), with SE decreasing to 1.909 D at T3. The rate of hyperopic reserve depletion in this group was markedly greater than that observed in the other trajectory classes. Accelerated consumption of hyperopic reserve is widely recognized as a critical precursor to myopia onset, and longitudinal evidence indicates that the cumulative incidence of insufficient hyperopic reserve increases with age and is strongly associated with the risk of developing myopia [23]. Despite having adequate initial hyperopic reserve, children in this trajectory experienced excessive depletion within only two years, suggesting a state of relatively rapid ocular axial elongation (“ocular overgrowth”). Without timely monitoring and intervention, these children may transition from physiological refractive development to pathological myopia. Therefore, this subgroup represents a key target population for early identification and proactive prevention strategies.

Slow refractive change group: a distinct high-risk population characterized by limited baseline hyperopic reserve

In the present study, 11.6% of children were classified into the slow refractive change group, which exhibited the lowest baseline SE value (T1 = −0.104 D), indicating minimal hyperopic reserve at study entry. Although the apparent rate of refractive change was relatively modest (slope = −0.164, $P < 0.001$), trajectory classification in LGMM is strongly influenced by baseline refractive status. Children with limited initial hyperopic reserve may demonstrate smaller absolute changes in SE but remain at elevated risk of myopia onset due to insufficient physiological buffering capacity.

Parental high myopia was strongly associated with reduced baseline hyperopic reserve. When baseline ocular parameters were not accounted for, parental myopia appeared to be a “protective factor” in the multinomial regression model, a finding inconsistent with established clinical evidence. To address the dependency of trajectory classification on baseline refractive status, a sensitivity analysis incorporating baseline axial length (AL) was performed. The results

demonstrated that each 1-mm increase in baseline AL was associated with a 2.57-fold increase in the odds of being classified into the rapid refractive change group (*OR* = 2.57, 95% *CI*: 1.91–3.46, *P* < 0.001).

These findings indicate that early elongation of axial length in preschool children is closely associated with accelerated refractive change and an increased risk of subsequent myopia. This result is consistent with the longitudinal findings reported by Yum et al. [24], who identified axial elongation as a key predictor of early-onset high myopia. Similarly, Sun et al. [25] reported that increased axial length in preschool children aged 3–6 years in Tongzhou District, Beijing, was significantly associated with early-stage pathological refractive development. Taken together, preschool children presenting with longer baseline axial length or limited hyperopic reserve represent a high-priority population for targeted monitoring and preventive intervention.

Determinants of latent trajectory membership in preschool refractive development

The present study identified baseline age, sex, parental moderate-to-high myopia (SE < −3.00 D), and daily outdoor activity duration as independent determinants of refractive trajectory classification. In contrast, no significant associations were observed for gestational age, birth weight, baseline BMI, picky eating behavior, or preference for sweet foods. These findings provide clinically relevant evidence supporting the early identification of children at elevated risk of myopia and facilitate the development of individualized prevention strategies.

Baseline age

Univariate analysis demonstrated a significant difference in baseline age distribution among the three trajectory groups (Kruskal–Wallis H = 11.149, *P* = 0.004). Multinomial regression analysis further indicated that increasing baseline age was associated with a lower likelihood of classification into both the stable refractive change group (OR = 0.683, P = 0.001) and the rapid refractive change group (OR = 0.615, P = 0.001), relative to the slow refractive change group. In other words, younger preschool children were more likely to exhibit trajectories characterized by more pronounced refractive changes.

This finding is consistent with established physiological patterns of ocular development. Axial length increases rapidly during infancy and early childhood, particularly before 3 years of age, after which the growth rate gradually decelerates and stabilizes toward adolescence [26]. Younger children typically exhibit less mature ocular regulatory mechanisms and greater susceptibility to rapid depletion of hyperopic reserve. When combined with environmental exposures, this may increase the likelihood of entering a rapid refractive progression trajectory.

Clinically, refractive monitoring in very young children is often insufficiently emphasized. The present findings suggest that children aged approximately 3 years represent a critical window for early screening. For children presenting with additional risk factors, early establishment of refractive records, shorter follow-up intervals, and timely preventive intervention are recommended. These findings are consistent with the principle of early monitoring and early intervention emphasized in the Technical Guidelines for Myopia Prevention and Control in Children and Adolescents (2018) [27].

Sex

Significant differences in sex distribution were observed across trajectory classes in univariate analysis (χ^2 = 6.518, *P* = 0.038). Multinomial regression analysis demonstrated that female children had a significantly higher likelihood of belonging to the rapid refractive change group compared with male children (*OR* = 2.207, *P* = 0.004). This observation is consistent with previous studies reporting sex-specific differences in refractive development [29].

Potential mechanisms may involve differences in ocular biometric development and hormonal regulation. Female children generally exhibit slightly smaller ocular dimensions, which may limit compensatory capacity during axial elongation and contribute to faster depletion of hyperopic reserve, particularly during late preschool years (4-5 years). However, sex was not significantly associated with membership in the stable refractive change group (*OR* = 1.331, *P* = 0.177), suggesting that sex-related effects may primarily influence the subgroup characterized by accelerated refractive change. These findings support the need for sex-specific considerations in precision prevention strategies.

Parental myopia

Multinomial regression analysis demonstrated that parental moderate-to-high myopia (SE < −3.00 D) was significantly associated with refractive trajectory classification. Relative to the slow refractive change group, paternal moderate-to-high myopia was associated with lower odds of classification into both the stable refractive change group (*OR* = 0.512, *P* = 0.019) and the rapid refractive change group (*OR* = 0.182, *P* < 0.001). Similarly, maternal moderate-to-high myopia was associated with reduced odds of classification into the stable refractive change group (*OR* = 0.350, *P* = 0.002) and the rapid refractive change group (*OR* = 0.252, *P* = 0.001).

Although these findings may appear inconsistent with the established association between parental myopia and increased offspring risk, they primarily reflect differences in baseline refractive status across trajectory classes. Children with highly myopic parents often present with reduced hyperopic reserve at baseline, resulting in trajectory classification into groups characterized by smaller absolute refractive change despite elevated long-term myopia risk. Previous studies have consistently demonstrated strong familial aggregation of myopia, with substantially higher incidence rates among children with myopic parents [29,30]. Genetic influences may regulate axial elongation dynamics and corneal curvature development, thereby modulating the emmetropization process. Consequently, parental myopia remains a critical risk indicator for early refractive monitoring.

Outdoor activity duration

Daily outdoor activity duration ≥ 2 hours was identified as a significant protective factor influencing refractive trajectory classification. Compared with children engaging in < 2 hours of daily outdoor activity, those with ≥ 2 hours exhibited substantially reduced likelihood of belonging to trajectory groups characterized by more pronounced refractive change. These findings are consistent with previous epidemiological evidence [13].

The protective effect of outdoor exposure may be mediated through increased light intensity stimulating retinal dopamine release, which inhibits excessive axial elongation. Given that the preschool period represents a critical window for refractive development, ensuring at least 2 hours of daily outdoor activity may effectively preserve hyperopic reserve and reduce the risk of myopia onset. These findings provide evidence-based support for both clinical counseling and public health interventions. Future studies should further investigate the effects of specific outdoor activity patterns, light intensity, and exposure duration on refractive trajectory heterogeneity.

Conclusions

Based on longitudinal LGMM, this study identified three distinct refractive development trajectories in preschool children: slow progression, stable progression, and rapid progression, revealing significant heterogeneity in early refractive development. Hospitals, families, and communities should collaborate to implement targeted predictive interventions through dynamic risk assessment, with priority given to continuous monitoring of high-risk subgroups—such as children with insufficient hyperopic reserve, parental myopia, and daily outdoor activity duration of less than 2 hours. For children with longer baseline axial length, establishing a refractive development archive is recommended to closely monitor refractive progression, and comprehensive strategies should be adopted to delay myopia onset. For children with stable refractive changes, regular monitoring remains essential. Future studies should establish a graded dynamic assessment system for myopia prevention and control in preschool children, tailoring interventions to trajectory-specific characteristics to achieve precise prevention and control of preschool myopia.

Study limitations

This study has several limitations. First, trajectory classification may have been dependent on baseline refractive status, as LGMM assigns substantial weight to baseline values. This could lead to the misclassification of children with insufficient baseline hyperopic reserve but rapid myopic progression into the slow-progression group; although baseline axial length was included for adjustment, classification bias could not be completely eliminated. Second, the observation period was only 2 years, which did not cover the critical transition period from preschool to primary school. This precluded verification of the long-term stability of the identified trajectories and their association with long-term myopic outcomes. Third, the sample was recruited from a single district in Beijing, representing a single-center regional population; therefore, caution should be exercised when generalizing the conclusions. Future studies with longer follow-up periods and multi-center designs are warranted to validate the findings of the present study.

Abbreviations

LGMM Latent Growth Mixture Model

SE Spherical equivalent ,

AL Axial length

CR Average corneal curvature

Declarations

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Authors' contributions

Hou J collected and cleaned the clinical data, performed statistical analyses, drafted the initial manuscript, and prepared all figures and tables. Jiao YH, Bian SM, Li Y , Ma ZF, Sha Y , Song W, reviewed the clinical data, interpreted the research results, and revised the manuscript critically for important intellectual content. Zhang WX conceptualized the study, designed the research protocol, supervised the entire study process, and finalized the manuscript. All authors have read and approved the final version of the manuscript and take responsibility for the integrity and accuracy of all parts of the work.

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Availability of data and materials

The datasets used and/or analyzed during the current study are available fromthe corresponding author on reasonable request.

Ethics and consent to participate

This study was approved by the Ethics Committee of Beijing Tongren Hospital, Capital Medical University (approval number: TRECK-Y2019-152).

Consent for publication

Not applicable in the article.

Competing interests

The authors declare no competing interests.

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Figures

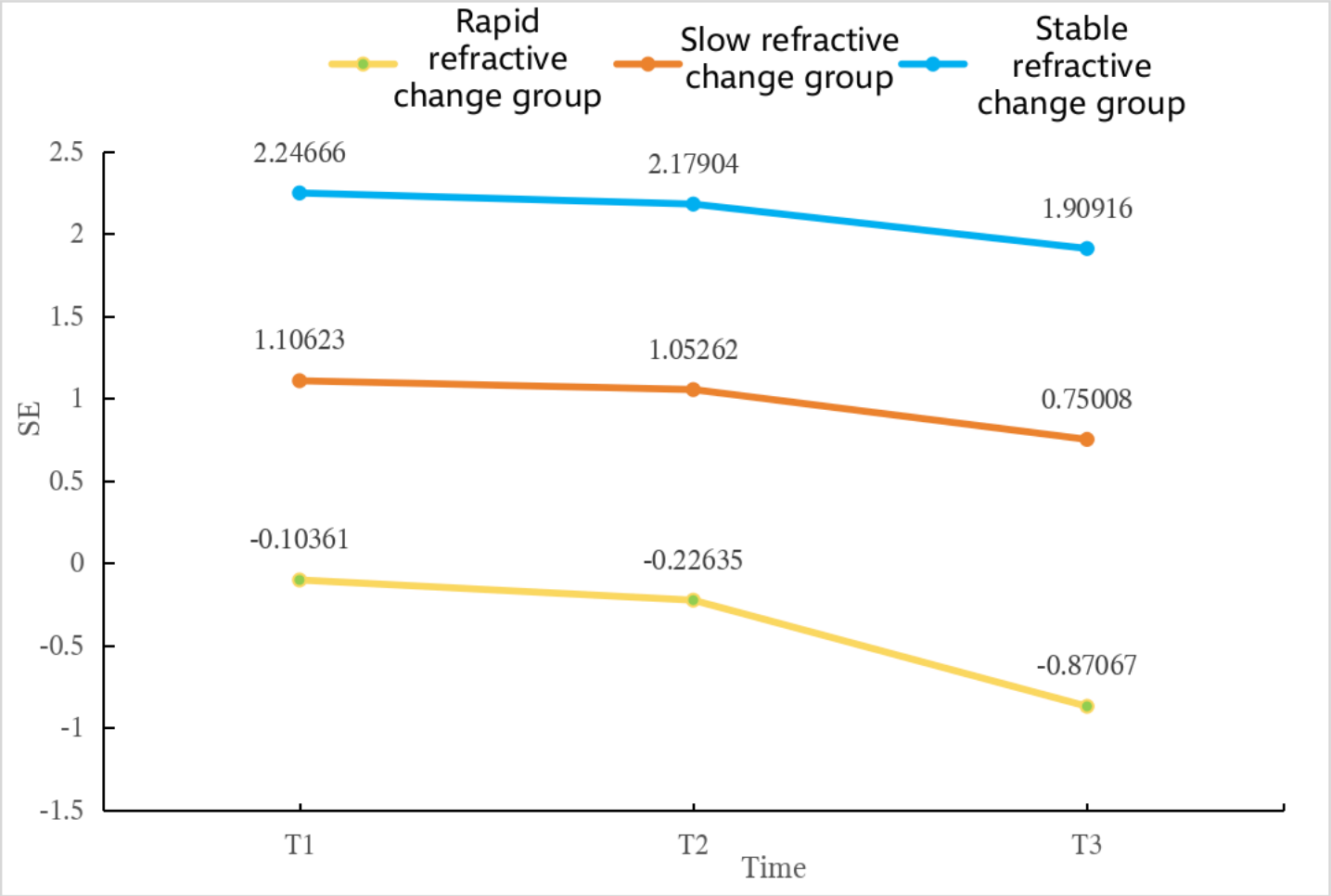


Figure 1

Heterogeneous trajectory plot of refractive change based on LGMM.The x-axis represents the follow-up time points (T1 = baseline survey, T2 = first year of follow-up, T3 = second year of follow-up); the y-axis represents SE refractive error (D).Rapid refractive change group (yellow line): T1 = -0.10361 D, T2 = -0.22635 D, T3 = -0.87067 D;Slow refractive change group (orange line): T1 = 1.10623 D, T2 = 1.05262 D, T3 = 0.75008 D;Stable refractive change group (blue line): T1 = 2.24666 D, T2 = 2.17904 D, T3 = 1.90916 D.