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Longitudinal associations between physical activity, positive psychological capital, and subjective well-being among rural left-behind children in China: a random-intercept cross-lagged panel model study

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Research Article

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Abstract

Background

Rural left-behind children in China, whose parents have both migrated to cities for work, face elevated risks to their mental health. Physical activity (PA) is a promising low-cost avenue for promoting their subjective well-being (SWB), but existing evidence is largely cross-sectional and cannot separate stable between-person differences from within-person change. We examined the longitudinal relations among PA, positive psychological capital (PPC), and SWB in rural left-behind children using a random-intercept cross-lagged panel model (RI-CLPM).

Methods

A four-wave longitudinal survey was conducted among 413 rural left-behind children in Grades 4–6 (52.3% boys) recruited by convenience sampling from three primary schools in Ji'an, Jiangxi Province, China. PA, PPC, and SWB were measured at four time points (T1–T4). We performed descriptive statistics, reliability analysis, Harman's single-factor test, Pearson correlations, and longitudinal measurement invariance tests, and fitted an RI-CLPM in Mplus 8.3. Indirect effects were tested with bias-corrected bootstrapping (5,000 resamples).

Results

At the between-person level, PA, PPC, and SWB were significantly and positively intercorrelated ($r = 0.438–0.474$, $p < 0.001$). At the within-person level, PA positively predicted subsequent PPC ($\beta = 0.158$ and 0.170, $p < 0.01$), whereas PPC did not significantly predict subsequent PA ($p > 0.10$). PPC positively predicted subsequent SWB across all three intervals ($\beta = 0.163$, 0.267, and 0.165, $p < 0.01$), and PA and SWB showed partially bidirectional cross-lagged effects. PPC significantly mediated the effect of PA on SWB from T1 to T3 (indirect effect = 0.045, 95% CI [0.003, 0.088]), whereas the reverse mediation was not significant.

Conclusions

PA was associated with higher SWB among rural left-behind children both directly and indirectly through the accumulation of PPC, and the PA → PPC → SWB pathway was the main direction of effect supported by the data. School-based interventions that promote physical activity may help sustain the psychological resources and well-being of left-behind children.

Background

With continued urbanisation, large numbers of rural labourers in China migrate to cities for work. Constrained by the household registration (hukou) system and the uneven distribution of educational resources, many are unable to bring their children with them, giving rise to a large population of rural left-behind children [1]. Growing up with prolonged parent–child separation places left-behind children at heightened risk to their mental health: loneliness, anxiety, and depressive symptoms are relatively common, and externalising problems such as aggression are more pronounced than among their non-left-behind peers [2, 3]. Subjective well-being (SWB)—an individual's overall evaluation of his or her quality of life according to self-set standards [4]—reflects how much positive experience a child possesses rather than merely whether psychological problems are present, and is therefore regarded as the

most representative positive indicator of mental health in this group [5]. Existing evidence indicates that left-behind children report significantly lower SWB than non-left-behind children, and that their SWB declines further as the duration of parental absence lengthens [6]. National policy has responded accordingly: the Three-Year Action Plan for Improving the Quality of Care Services for Rural Left-Behind Children and Children in Difficult Circumstances, issued by the Ministry of Civil Affairs together with 14 other departments, lists psychological care as a key task [7], and the Ten Measures for Further Strengthening Mental Health Work in Primary and Secondary Schools issued by the General Office of the Ministry of Education require that left-behind children and other vulnerable student groups be registered and provided with individualised ("one student, one plan") mental health support [8]. Given that parent–child separation is unlikely to change in the short term, identifying modifiable factors that can effectively raise the SWB of left-behind children has become an urgent practical issue.

Physical activity (PA) is a low-cost and highly accessible health-promotion strategy with important benefits for mental health: regular exercise not only improves physical fitness but also regulates emotion by promoting the secretion of pleasure-related hormones such as dopamine and endorphins, thereby alleviating anxiety and depression [9]. At the national level, the notion of "strengthening the mind through the body" has been repeatedly emphasised: the Special Action Plan for Comprehensively Strengthening and Improving Student Mental Health in the New Era (2023–2025) explicitly calls for harnessing the emotion-regulation and stress-relief functions of sport [10], and both the Opinions on Implementing the Student Physical Fitness Strengthening Plan [11] and the Three-Year Action Plan for Popularising Scientific Fitness and Exercise Interventions among Adolescents (2026–2028) [12] identify mental health as a priority for intervention. For left-behind children in particular, PA may partly compensate for the absence of family emotional support by providing an alternative channel for emotional release and interpersonal interaction [13]. The link between PA and SWB is especially direct. Psychologically, exercise offers a route for emotion regulation and stress release, generating positive affect such as pleasure and satisfaction; physiologically, regular exercise enhances well-being through the secretion of endorphins and dopamine; and socially, teamwork and peer interaction help build supportive interpersonal networks, while social support is itself an important source of SWB [14]. Longitudinal evidence further suggests a bidirectional relationship between adolescents' physical activity and life satisfaction [15], and meta-analytic evidence supports a stable association between physical activity and affective well-being [16]. Overall, the positive association between PA and SWB is well supported, but most of this evidence comes from general adolescent and adult samples, and whether it holds for children whose parents have both migrated remains to be tested specifically.

Positive psychological capital (PPC) is a positive psychological state, developed over the course of individual growth, that comprises self-efficacy, resilience, hope, and optimism [17]; it is regarded as an important protective factor for the psychological adjustment and social adaptation of left-behind children. With respect to PA and PPC, sport provides fertile ground for the development of psychological capital: through cooperative communication and healthy competition, individuals develop gratitude and perseverance, and by mastering motor skills they gain confidence, which in turn enhances self-efficacy, resilience, hope, and optimism [18]. Research on left-behind children has likewise found that PA is significantly and positively associated with PPC [19]. With respect to PPC and SWB, PPC reliably enhances SWB [20] and mediates the relationship between family socioeconomic status and adolescents' well-being [21]. Linking the three variables, existing work suggests that the sense of achievement and social experience derived from PA can be further converted into higher levels of well-being through the accumulation of PPC [19]. According to conservation of resources theory, PA is a form of resource investment, and the psychological capital accumulated through exercise can be converted into well-being gains, forming a "PA–PPC–SWB" gain chain [22]. However, studies examining these three variables together have mostly used cross-sectional designs, and the temporal direction of their relations still requires testing with longitudinal data.

Taken together, existing research has the following limitations. First, most studies have focused on general adolescents or university students, with insufficient attention to left-behind children whose parents have both migrated. Second, cross-sectional designs predominate, so the temporal ordering and direction of effects remain unclear. Third, traditional cross-lagged panel models cannot separate stable between-person differences from within-person dynamics, which may bias estimates. Although previous studies have largely observed positive pairwise correlations at the between-person level [19, 20], these relations have not been systematically examined within a unified longitudinal framework. The random-intercept cross-lagged panel model (RI-CLPM) decomposes each variable's observed scores into between-person and within-person components and specifies cross-lagged paths only at the within-person level, thereby overcoming these limitations and allowing temporal relations to be examined more rigorously [23]. Accordingly, the present study recruited 413 rural left-behind children and used four waves of longitudinal data to examine the relations among PA, PPC, and SWB while distinguishing between-person from within-person effects. We proposed the following hypotheses:

(1) H1: at the between-person level, PA, PPC, and SWB are significantly and positively correlated with one another.

(2) H2a: at the within-person level, PA and subsequent SWB positively predict each other; H2b: PA at an earlier time point positively predicts subsequent PPC.

(3) H3: PPC mediates the effect of PA on SWB; that is, PA promotes SWB by increasing PPC.

Methods

Participants

Using convenience sampling, we recruited students in Grades 4, 5, and 6 from three primary schools in Ji'an City, Jiangxi Province, China, and conducted a four-wave longitudinal survey using paper-and-pencil questionnaires. A total of 1,500 questionnaires were distributed. After screening, invalid questionnaires (e.g., patterned responding, careless completion, and missing or erroneous entries) were removed, yielding 1,296 valid questionnaires (valid response rate 86.4%). Within this valid sample, item-level screening identified 417 children whose parents had both migrated for work; of these, 413 who completed all four waves and whose names and classes could be matched consistently across waves constituted the final analytic sample. To assess whether attrition was random, independent-samples t-tests comparing attrited and retained participants showed no significant differences in PA ($t = -0.814$, $p > 0.05$), PPC ($t = -0.059$, $p > 0.05$), or SWB ($t = -0.028$, $p > 0.05$), indicating no systematic attrition. The demographic characteristics of the sample are presented in Table 1: 216 boys (52.3%) and 197 girls (47.7%); 136 fourth-graders (32.9%), 130 fifth-graders (31.5%), and 147 sixth-graders (35.6%).

Table 1
Sample characteristics

Variable	Category	n	%
Gender	Boys	216	52.3
	Girls	197	47.7
Grade	Grade 4	136	32.9
	Grade 5	130	31.5
	Grade 6	147	35.6
Total		413	100.0

Measures

Physical activity. The Physical Activity Questionnaire developed by Li et al. [24] was used. It integrates the core dimensions of the Physical Activity Rating Scale-3 (PARS-3) revised by Liang [25] and extends the measurement of the psychological and social attributes of physical activity. The scale contains seven items that quantify PA level along three dimensions—exercise intensity, duration, and frequency—and additionally covers four dimensions: exercise attitude, cognitive level, initiative in participation, and post-exercise experience. Items are rated on a 5-point Likert scale, with higher total scores indicating a better physical activity status. In the present study, the internal consistency coefficients across the four waves were 0.860 (T1), 0.873 (T2), 0.876 (T3), and 0.860 (T4).

Subjective well-being. The Adolescents' Subjective Well-Being Scale developed by Zhang et al. [26] was used. It comprises two subscales, life satisfaction and happiness. The life satisfaction subscale covers six dimensions—friendship, family, school, environment, freedom, and academic performance—with 36 items rated on a 7-point scale from 1 ("completely untrue of me") to 7 ("completely true of me"); higher scores indicate higher SWB. Cronbach's α across the four waves was 0.927 (T1), 0.927 (T2), 0.931 (T3), and 0.896 (T4).

Positive psychological capital. The Positive PsyCap Questionnaire (PPQ) developed by Zhang et al. [27] was used. It contains 26 items covering four dimensions—self-efficacy, resilience, hope, and optimism—rated on a 7-point scale from 1 ("completely untrue of me") to 7 ("completely true of me"), with higher scores indicating higher PPC. Cronbach's α across the four waves was 0.936 (T1), 0.938 (T2), 0.944 (T3), and 0.940 (T4).

Procedure

This study was reviewed and approved by the Ethics Committee of the School of Physical Education, Jiangxi Normal University (approval no. IRB-JXNU-PEC-20251001), under the title "A longitudinal study of the effects of physical activity on the psychological flourishing of rural left-behind children". After obtaining informed consent from the schools, the guardians (legal representatives), and the students themselves, trained research assistants administered the questionnaires to whole classes. A standardised set of instructions was used at each wave to explain how to complete the questionnaire and what to pay attention to, and the questionnaires were collected on site. To reduce common method bias, responses were anonymous and participants were assured that there were no right or wrong answers.

Data analysis

First, SPSS 26.0 was used for descriptive statistics, scale reliability analysis, common method bias testing (Harman's single-factor test), and Pearson correlations among the variables. Mplus 8.3 was then used to construct an RI-CLPM examining the longitudinal relations among PA, PPC, and SWB.

In specifying the model, an RI-CLPM containing PA, PPC, and SWB was built directly, incorporating the autoregressive paths of each variable, the cross-lagged paths among the three variables, and their within-time correlations, so that both unidirectional and bidirectional dynamic relations could be tested simultaneously. The significance of the indirect effects was tested using bias-corrected percentile bootstrapping with 5,000 resamples; an indirect effect was deemed significant if the 95% confidence interval did not include zero. Before model fitting, single-measure intraclass correlation coefficients (ICCs) for the four waves of PA, PPC, and SWB were computed with individuals as the grouping unit, in order to quantify the proportion of variance attributable to stable between-person differences: if such differences are non-negligible, estimates from a traditional cross-lagged panel model conflate effects at the two levels, whereas the RI-CLPM explicitly absorbs between-person variance through random intercepts and is therefore appropriate for data of this kind.

Results

Common method bias

All data were collected by self-report. To test for possible common method bias, Harman's single-factor test was applied separately to the questionnaire data at each of the four time points. At T1–T4, the number of common factors with eigenvalues greater than one was 12 at each wave, and the variance explained by the first common factor was 17.70%, 21.45%, 22.29%, and 21.60%, respectively—all below the 40% threshold.

Descriptive statistics and repeated-measures analysis

Descriptive statistics for the three variables across the four waves are presented in Table 2. To examine how each variable changed over time, a one-way repeated-measures analysis of variance was conducted with measurement occasion (T1–T4) as the within-subject factor. The results showed that the effect of time was significant for all three variables (PA: $F = 9.15$; PPC: $F = 6.74$; SWB: $F = 27.13$; all $p < 0.001$), indicating significant change over the four waves.

Table 2
Descriptive statistics of the study variables across the four waves

Variable	T1 (M ± SD)	T2 (M ± SD)	T3 (M ± SD)	T4 (M ± SD)	F	p
Physical activity	3.46 ± 0.77	3.50 ± 0.80	3.39 ± 0.81	3.28 ± 0.82	9.15	< 0.001
Positive psychological capital	4.13 ± 0.95	4.23 ± 0.94	4.21 ± 0.99	4.33 ± 0.96	6.74	< 0.001
Subjective well-being	3.98 ± 0.81	3.98 ± 0.81	4.04 ± 0.83	3.73 ± 0.70	27.13	< 0.001

Note. M = mean; SD = standard deviation. One-way repeated-measures ANOVAs with measurement occasion (T1–T4) as the within-subject factor.

In addition, treating individuals as the grouping unit and the four occasions as measurement indicators, we computed single-measure intraclass correlation coefficients (ICCs) for the three variables based on a two-way mixed-effects model with absolute agreement. The ICCs were 0.383 (95% CI [0.332, 0.436]) for PA, 0.513 (95% CI [0.464, 0.562]) for PPC, and 0.523 (95% CI [0.469, 0.575]) for SWB, all significantly greater than zero ($p < 0.001$). Stable between-person differences thus accounted for 38.3%, 51.3%, and 52.3% of the total variance in PA, PPC, and SWB, respectively, while a substantial proportion of the variance remained attributable to within-person fluctuation over time. Comparatively, the between-person stable component was larger for SWB and PPC, consistent with their nature as a relatively stable psychological resource and an overall evaluative judgement, whereas the within-person component was relatively larger for PA, suggesting that exercise behaviour is more susceptible to situational influences. This pattern indicates that ignoring between-person differences and applying a traditional cross-lagged panel model would conflate effects at the two levels, providing the methodological rationale for using the RI-CLPM in this study [23].

Correlation analysis

Table 3 presents the correlations among PA, PPC, and SWB across the four time points. All variables were significantly and positively intercorrelated ($p < 0.01$), providing a basis for the subsequent RI-CLPM. With respect to stability, the cross-time correlations of each variable were moderate to high: 0.35–0.57 for PA, 0.51–0.65 for PPC, and 0.42–0.68 for SWB, indicating that all three variables showed a degree of cross-time stability. Contemporaneous associations were also evident; for example, $r = 0.40$ between PA and SWB at T2 and $r = 0.51$ between PPC and SWB at T4. Cross-lagged correlations between adjacent occasions were generally significant as well; for example, T1 PA with T2 PPC ($r = 0.21$), T2 PPC with T3 SWB ($r = 0.40$), and T3 PA with T4 SWB ($r = 0.37$). Overall, the variables showed both within-person cross-time stability and contemporaneous and prospective associations with one another, suggesting dynamic longitudinal relations that warrant further examination of their directionality using a cross-lagged model.

Table 3
Correlations among physical activity, positive psychological capital, and subjective well-being across the four waves

Variable	T1 PA	T1 PPC	T1 SWB	T2 PA	T2 PPC	T2 SWB	T3 PA	T3 PPC	T3 SWB	T4 PA	T4 PPC
T1 PA	1										
T1 PPC	.27**	1									
T1 SWB	.16**	.16**	1								
T2 PA	.35**	.21**	.33**	1							
T2 PPC	.31**	.65**	.23**	.26**	1						
T2 SWB	.22**	.26**	.59**	.40**	.36**	1					
T3 PA	.34**	.16**	.17**	.42**	.23**	.19**	1				
T3 PPC	.26**	.36**	.13**	.28**	.56**	.28**	.29**	1			
T3 SWB	.22**	.24**	.42**	.36**	.40**	.59**	.31**	.36**	1		
T4 PA	.28**	.15**	.18**	.36**	.18**	.17**	.57**	.24**	.36**	1	
T4 PPC	.24**	.39**	.23**	.27**	.54**	.29**	.36**	.60**	.44**	.36**	1
T4 SWB	.21**	.21**	.47**	.33**	.34**	.51**	.37**	.36**	.68**	.42**	.51**

Note. PA = physical activity; PPC = positive psychological capital; SWB = subjective well-being. ** $p < 0.01$.

Longitudinal measurement invariance

A stepwise constraint approach was used to test the longitudinal measurement invariance of the PA, PPC, and SWB scales across the four measurement occasions. As shown in Table 4, all three scales fitted the data well under configural, weak (equal factor loadings), and strong (equal intercepts) invariance (CFI ≥ 0.947, RMSEA ≤ 0.026, SRMR ≤ 0.036), and the changes in fit between successive levels were small (ΔCFI ≤ 0.003 and ΔRMSEA ≤ 0.001 for all comparisons). These results indicate that all three scales achieved strong invariance and were comparable across time, satisfying the prerequisites for the subsequent RI-CLPM analysis.

Table 4
Longitudinal measurement invariance of the three scales across the four waves

Scale	Model	χ^2	df	CFI	TLI	RMSEA (90% CI)	SRMR	ΔCFI	ΔRMSEA
Physical activity	Configural	405.734	322	0.988	0.986	0.025 [0.017, 0.032]	0.027	—	—
	Weak	423.552	337	0.987	0.986	0.025 [0.017, 0.032]	0.031	0.001	0.000
	Strong	460.815	358	0.985	0.984	0.026 [0.019, 0.033]	0.036	0.002	0.001
Positive psychological capital	Configural	6567.807	5132	0.957	0.955	0.026 [0.024, 0.028]	0.032	—	—
	Weak	6637.838	5198	0.956	0.955	0.026 [0.024, 0.028]	0.033	0.001	0.000
	Strong	6747.802	5276	0.955	0.955	0.026 [0.024, 0.028]	0.035	0.001	0.000
Subjective well-being	Configural	11959.918	9876	0.951	0.949	0.023 [0.021, 0.024]	0.033	—	—
	Weak	12067.149	9966	0.950	0.949	0.023 [0.021, 0.024]	0.034	0.001	0.000
	Strong	12296.728	10074	0.947	0.946	0.023 [0.022, 0.025]	0.036	0.003	0.000

Note. Configural/weak/strong = configural, weak (equal factor loadings), and strong (equal intercepts) invariance.

Random-intercept cross-lagged panel model

Model fit and between-person correlations. Mplus 8.3 was used to construct the RI-CLPM examining the relations among PA, PPC, and SWB at both the between- and within-person levels. The model fitted the data well (CFI = 0.994, TLI = 0.983, SRMR = 0.026, RMSEA = 0.035). As shown in Fig. 1, at the between-person level PA, PPC, and SWB were significantly intercorrelated (r = 0.438–0.474, p < 0.001), indicating a stable pattern of co-variation among the three variables.

Within-person cross-lagged effects. At the within-person level, PA positively predicted PPC over time (β = 0.158 and 0.170, p < 0.01), whereas PPC did not significantly predict PA at the next time point (β = 0.088, 0.126, and −0.006, p > 0.10). Second, PPC positively predicted SWB over time (β = 0.163, 0.267, and 0.165, p < 0.01); conversely, SWB significantly and positively predicted PPC only from T3 to T4 (β = 0.303, p < 0.001), with the other two intervals failing to reach significance (β = 0.105 and 0.092, p > 0.05). Finally, partially bidirectional cross-lagged effects were observed between PA and SWB: PA at T2 and T3 positively predicted SWB at T3 and T4, respectively (β = 0.145 and

0.175, p < 0.01), and SWB at T1 and T3 positively predicted PA at T2 and T4, respectively (β = 0.254 and 0.241, p < 0.001).

Longitudinal mediation. The longitudinal mediation tests showed that, for the prediction of T3 SWB from T1 PA, the indirect effect through T2 PPC was 0.045 (95% CI [0.003, 0.088]); because the confidence interval excluded zero, this effect was statistically significant, indicating that PPC partially mediated the longitudinal prediction of SWB by PA. For the prediction of T4 SWB from T2 PA, the indirect effect through T3 PPC was 0.014 (95% CI [− 0.005, 0.032]); the confidence interval included zero and the effect was not statistically significant. The reverse mediation test showed that, for the prediction of T3 PA from T1 SWB, the indirect effect through T2 PPC was 0.014 (95% CI [− 0.012, 0.039]); the confidence interval included zero and the effect was not statistically significant (Table 5).

Table 5
Indirect effects of physical activity on subjective well-being through positive psychological capital

Indirect pathway	Estimate	95% CI	Significant
T1 PA → T2 PPC → T3 SWB	0.045	[0.003, 0.088]	Yes
T2 PA → T3 PPC → T4 SWB	0.014	[− 0.005, 0.032]	No
T1 SWB → T2 PPC → T3 PA (reverse)	0.014	[− 0.012, 0.039]	No

Note. Bias-corrected percentile bootstrapping with 5,000 resamples. PA = physical activity; PPC = positive psychological capital; SWB = subjective well-being.

Discussion

Stable between-person associations among the three variables

At the between-person level, PA, PPC, and SWB were significantly and positively intercorrelated (r = 0.438–0.474, p < 0.001), supporting H1. This indicates that, throughout the follow-up period, left-behind children with higher levels of PA tended also to possess richer PPC and higher SWB. This finding corroborates previous research among left-behind children and is consistent with the view that PPC effectively supports their psychological adaptation [28]. Conservation of resources theory offers an explanation: individuals tend to acquire, retain, and accumulate the resources they value, and resources exhibit joint gain effects, such that those with richer initial resources are more likely to obtain further resource increments, forming a “gain spiral” [22]. Left-behind children with higher levels of PA accumulate physical, psychological, and social resources that are interrelated and mutually reinforcing, and consequently PA, PPC, and SWB co-vary significantly at the between-person level. This echoes the findings of Fan et al. [29], who showed that psychological capital buffers the adverse effects of life stress on the loneliness and well-being of left-behind children and constitutes an important personal resource for maintaining their psychological adaptation. In terms of effect size, these correlations are moderate to substantial and comparable in magnitude to the associations between physical activity, psychological capital, and SWB reported in previous cross-sectional studies [19, 20]. Considering that our participants were left-behind children whose parents had both migrated and whose family emotional support was almost entirely absent, this stable co-variation also suggests that positive indicators such as PA, PPC, and SWB tend to co-occur and to be mutually dependent in this high-risk group. It should be noted, however, that between-person correlations reflect only co-variation at the level of stable traits and cannot answer the question of “who influences whom”; if children who exercise more also happen to have better family environments and personality foundations, simple correlations may overestimate the independent

effect of PA. This is precisely why the present study used the RI-CLPM to examine the three variables further at the within-person level [23].

Dynamic within-person relations among the three variables

At the within-person level, the model revealed dynamic predictions among the three variables over time. First, PA positively predicted PPC over time (β = 0.158 and 0.170, p < 0.01), supporting H2b, whereas PPC failed to significantly predict PA in any of the three intervals. This asymmetric result suggests that PA drives the development of psychological capital rather than the reverse. By mastering motor skills, children gain successful experiences, and through cooperation and competition with peers they gain acceptance and recognition, gradually accumulating psychological resources such as self-efficacy, resilience, hope, and optimism [18]. Notably, the coefficients obtained here (β = 0.158–0.170) represent net within-person effects after stable between-person differences have been removed; they are more conservative than the simple correlations reported in cross-sectional studies [19], yet remain robustly significant, providing longitudinal support for the inference that PA is an important source of psychological capital. This also accords with evidence from large samples showing that PA significantly promotes adolescents' mental health and that social experiences such as peer interaction constitute an important mechanism [30].

Second, all three cross-lagged paths from PPC to SWB were significant (β = 0.163, 0.267, and 0.165, p < 0.01), making this the most stable pathway in the model and further confirming the central role of psychological resource accumulation in enhancing well-being. The reverse prediction from SWB to PPC was significant only in the third interval (β = 0.303, p < 0.001), indicating that the development of psychological capital derives mainly from prior exercise experience and resource accumulation, although when children are in a positive emotional state their psychological capital can also be nourished to some extent.

Finally, PA and SWB showed partially bidirectional cross-lagged effects: PA at T2 and T3 positively predicted SWB at T3 and T4, respectively (β = 0.145 and 0.175, p < 0.01), and SWB at T1 and T3 positively predicted PA at T2 and T4, respectively (β = 0.254 and 0.241, p < 0.001), supporting H2a. This suggests a potentially mutually reinforcing cycle between exercise and well-being: exercise improves children's mood and makes their experience of life more positive, while children with higher well-being have more energy and greater confidence in exercise and are therefore more willing to persist. It should be noted, however, that the occasions on which the two directions were significant did not fully correspond, and some intervals showed no significant prediction. In other words, this mutual reinforcement did not occur consistently at every stage; we therefore describe it as a partially bidirectional dynamic predictive relationship, which is consistent with meta-analytic evidence on physical activity and affective well-being [16].

Fredrickson's broaden-and-build theory [31] provides theoretical support for these dynamic relations: the positive emotional experiences induced by PA can broaden left-behind children's thought–action repertoires and, through sustained exercise experience, enhance their confidence, competence, and social interaction, thereby increasing SWB. Likewise, according to the upward spiral theory of positive emotions proposed by Fredrickson and Joiner [32], positive emotion, positive cognition, and positive behaviour mutually evoke one another in an upward spiral; individuals with higher SWB experience more positive emotions and are therefore more willing to engage in PA. This precisely explains the partially bidirectional dynamic relationship observed between PA and SWB in the present study. In addition, self-determination theory indicates that PA contexts naturally afford opportunities to satisfy the three basic psychological needs for competence, autonomy, and relatedness [33], providing a motivational explanation for the sustained within-person prediction of PPC by exercise. Research has shown that autonomous

motivation formed by satisfying these needs not only prompts individuals to initiate and maintain long-term PA, but also has indirect and longer-term effects on emotional experience and mental health [34].

In addition, the autoregressive results showed that PPC and SWB changed relatively smoothly within individuals, whereas PA was less stable in the earlier waves. This suggests that children's exercise behaviour is more susceptible to situational influences such as the progression of the school term, weather, and academic pressure [35], and also indicates that children cannot readily sustain exercise on their own; exercise interventions therefore need to be supported by external institutional arrangements involving schools and families.

The longitudinal mediating role of positive psychological capital

The mediation tests showed that, for the prediction of T3 SWB from T1 PA, the indirect effect through T2 PPC was significant (0.045, 95% CI [0.003, 0.088]), supporting H3, whereas the indirect effect from T2 PA through T3 PPC to T4 SWB was not significant (0.014, 95% CI [− 0.005, 0.032]). The reverse mediation path (T1 SWB – T2 PPC – T3 PA) was likewise not significant (0.014, 95% CI [− 0.012, 0.039]). Together, these results indicate that "PA → PPC → SWB" is the main direction of effect supported among the three variables.

This result shows that the mediation effect remained significant after controlling for autoregressive effects and within-time correlations, demonstrating that the promotive effect of PA on SWB is partly achieved through the accumulation of psychological capital rather than being confounded by stable individual differences [14]. The mediation effect appeared mainly in the first window and weakened in later waves, which may be related to hedonic adaptation [36]: this account holds that individuals' emotional levels fluctuate around a relatively stable baseline, and that after an external stimulus produces a positive or negative deviation, individuals gradually habituate to and adapt to that stimulus over time, reconstructing their cognition and interpretation of its impact on their lives, so that emotion or well-being gradually returns to its original level [37, 38]. In other words, exercise may bring relatively pronounced psychological benefits initially, but as time passes children gradually habituate to these benefits, or their psychological capital stabilises, and the mediating effect correspondingly weakens. It should be noted that hedonic adaptation mainly concerns constant and unchanging stimuli, and that adaptation is usually partial rather than complete. As an activity-based stimulus whose content continually changes and which involves the acquisition of new skills and peer interaction, PA readily evades the adaptation process, and its direct effect remained significant across all time windows in the present study; the weakening of the mediation effect is therefore more likely to reflect a diminishing marginal contribution of a single transformation pathway rather than the disappearance of the benefits of exercise [39].

This longitudinal mediation evidence can be contrasted with previous cross-sectional studies: among general junior high school students, PA significantly and positively predicts SWB, with perceived social support and exercise self-efficacy acting as partial mediators [40]; among left-behind children, psychological capital likewise mediates the relationship between physical activity and social anxiety [19].

Limitations

Several limitations should be noted. First, all variables were measured by self-report; although Harman's single-factor test indicated no serious common method bias, responses may still be affected by social desirability and recall bias. Second, although four waves of data support the temporal ordering of the variables, they cannot establish causality as rigorously as experimental or intervention designs. Third, participants were recruited by convenience sampling from three primary schools in a single city and were restricted to children in Grades 4–6 whose parents had both migrated; the generalisability of the findings to other regions, age groups, and other forms

of parental absence remains to be tested. Future research could combine multi-informant reports with school-based exercise interventions to examine the causal effects of PA on PPC and SWB among left-behind children.

Conclusions

This study of 413 rural left-behind children whose parents had both migrated for work used four waves of longitudinal data and an RI-CLPM to examine the longitudinal relations among PA, PPC, and SWB while distinguishing between-person from within-person effects. The main conclusions are as follows.

(1) At the between-person level, PA, PPC, and SWB were significantly and positively intercorrelated, indicating stable synergistic co-variation among the three variables in this population; H1 was supported. Left-behind children with higher levels of PA tended also to have richer positive psychological resources and higher well-being, and positive indicators tended to co-occur and to be mutually dependent in this high-risk group.

(2) At the within-person level, PA positively predicted subsequent PPC and SWB over time, and PPC reliably and positively predicted subsequent SWB; PA and SWB showed a partially bidirectional predictive relationship. H2b was supported and H2a was partially supported. After stable between-person differences were removed, PA still drove the dynamic development of psychological resource accumulation and well-being enhancement.

(3) PPC partially mediated the prediction of subsequent SWB by PA at the preceding time point; H3 was partially supported. The reverse mediation path was not significant, suggesting that "PA → PPC → SWB" is the main validated direction of effect among the three variables, consistent with the resource accumulation and gain process described by conservation of resources theory.

Abbreviations

PA
Physical activity
PPC
Positive psychological capital
SWB
Subjective well-being
RI-CLPM
Random-intercept cross-lagged panel model
ICC
Intraclass correlation coefficient
CI
Confidence interval
PARS-3
Physical Activity Rating Scale-3
PPQ
Positive PsyCap Questionnaire
CFI
Comparative fit index
TLI
Tucker–Lewis index

RMSEA
Root mean square error of approximation
SRMR
Standardized root mean square residual

Declarations

Ethics approval and consent to participate

This study was approved by the Ethics Committee of the School of Physical Education, Jiangxi Normal University (approval no. IRB-JXNU-PEC-20251001). The study was conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from the parents or legal guardians of all participating children, and assent was obtained from the children themselves; the schools also granted permission for the study.

Consent for publication

Not applicable. This manuscript does not contain any individual person's data in any identifiable form.

Availability of data and materials

The datasets generated and analysed during the current study are not publicly available because they contain information that could compromise the privacy of minor participants, but are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' contributions

Xin Xiong: conceptualisation, methodology, formal analysis, data curation, visualisation, writing – original draft, writing – review and editing. Qingyao Ke: conceptualisation, methodology, formal analysis, data curation, visualisation, writing – original draft, writing – review and editing. Wu Ouyang: investigation, resources, project administration. All authors read and approved the final manuscript.

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Figures

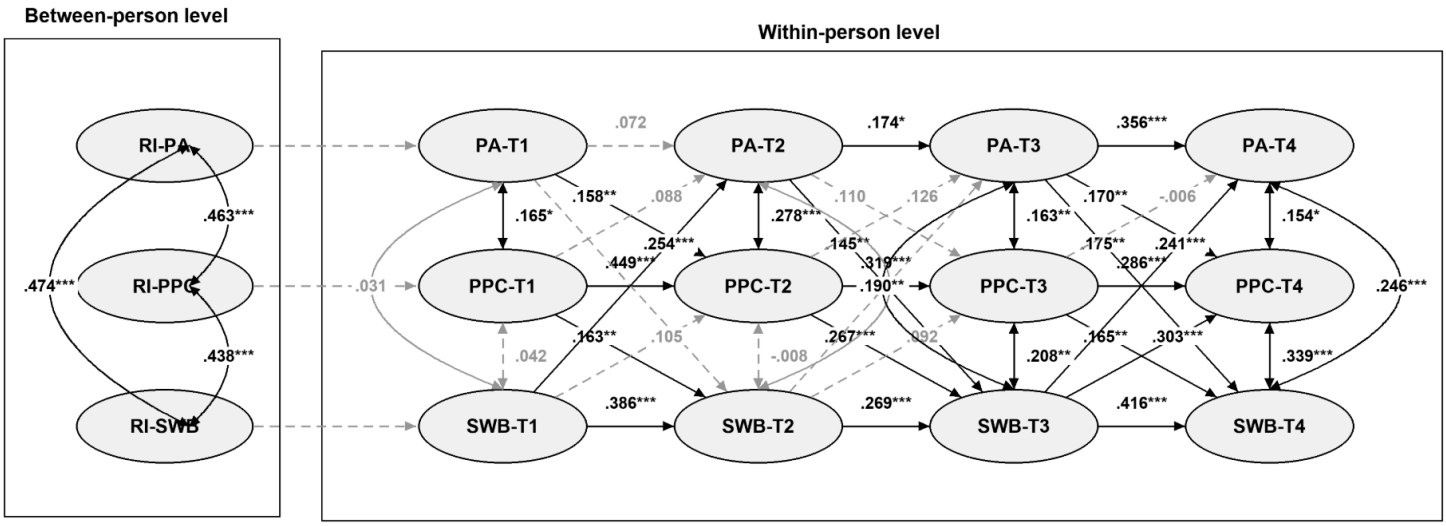


Figure 1

Random-intercept cross-lagged panel model of physical activity, positive psychological capital, and subjective well-being across four waves. Solid arrows indicate significant paths ($p < 0.05$) and dashed arrows indicate non-significant paths; double-headed arrows represent correlations. PA = physical activity; PPC = positive psychological capital; SWB = subjective well-being; RI = random intercept (between-person component); T1–T4 = measurement occasions. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.