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Abstract

Background: Maintaining and optimising intrinsic capacity (IC) across a person's life course is a core component of the World Health Organization's model of healthy ageing. However, the contribution of cumulative health inequalities over time to subtle changes in IC in late life is not well understood.

Methods: We included 21,783 participants aged 45+ from the China Health and Retirement Longitudinal Study and calculated a validated prognostic value of IC. We included eleven early-life factors to investigate their direct influence on IC over thirty years later and cumulative influence through four current socioeconomic factors. We used multivariable linear regression and concentration index decomposition to investigate the contributions of each determinant to IC inequalities. Mediation analysis identified the direct and cumulative contribution of early-life factors.

Results: Participants with an advantaged environment in childhood and a higher current socioeconomic position had a significantly higher IC score. This inequality was greatest for cognitive capacity and sensory capacity. Overall, early-life factors directly explained 13.92% (95% CI: 12.07% to 15.77%) of IC inequalities, while 28.57% (95% CI: 28.19% to 28.95%) of IC inequalities were explained through the cumulative effects of socioeconomic inequalities over a person's life course.

Conclusion: In China, unfavourable early-life factors appear to directly decrease late-life health status, particularly cognitive and sensory capacities rather than locomotor functioning, psychological capacity or homeostasis, and these effects are exacerbated by the cumulative socioeconomic inequalities over a person's life course. Interventions in early life and subsequently across the life course may be effective in reducing these disparities.

Keywords: intrinsic capacity, healthy ageing, life course inequality, cognition, China

Introduction

The complexity of health status in older age means that traditional disease-based conceptualisations or health metrics based on single domains are inadequate proxies for the health of older adults [1]. Recognising that *healthy ageing* matters to everyone, the World Health Organization (WHO) used a capabilities approach to frame healthy ageing in the broadest possible sense in its 2015 *World report on ageing and health* [1,2]. According to this framework, healthy ageing is experienced when the 'functional ability' to be and do the things a person values is developed, maintained and optimised across a person's life course. Functional ability has many dimensions, including being able to meet one's basic needs, to learn, grow and make critical decisions, to be actively mobile, to build and maintain meaningful relationships, and to contribute to society [3]. This ability is determined by a person's intrinsic capacity (IC), the environment they live in, and the interaction between the individual and their environment [1].

IC comprises all of the individual-level bio-psychological capacities that a person can draw on, and developing and maintaining these attributes across a person's life course is critical to healthy ageing [4]. Building on gerontological and disability theory [5], IC reflects the biological capacities of an organism rather than its impairments or deficits, a strengths-based approach distinct from, but complementary to, concepts such as frailty [6,7]. Although IC has been increasingly adopted by clinicians and researchers, its use remains inconsistent [8–13]. Nonetheless, the IC construct and its prognostic value have been successfully validated and empirically examined in longitudinal analyses of English [14] and Chinese cohorts [15].

IC is unique and different from other ageing metrics in several ways. First, it provides a fine-grained and comprehensive measure of overall health rather than an impairment of specific body functions [16]. Second, it indicates a shift from a disease-oriented to a functioning-oriented approach from the traditional disease-centred approach[17]. Finally, it distinguishes individual attributes of functioning from the influence of the environment. These characteristics facilitate cross-time, cross-country and cross-culture comparisons of healthy ageing and the investigation of the contextual attributes that may either impact IC or, in conjunction with IC, contribute to an individual's functional ability. It has been suggested that regular monitoring of IC could predict negative health outcomes among older adults in the UK [14], China [15] and the USA [16], and thus IC could be an early warning system informing preventive interventions [15,16,18].

Across an individual's life, IC is shaped by many factors, including underlying physiological and psychological changes, health-related behaviour and the presence or absence of disease [3]. Ageing describes a natural process that commences early in life [19] and is influenced by socioeconomic and physical determinants that are present at different life stages. Moreover, disadvantages in nutrition, health, wealth, education, employment and income that arise early in life can reinforce each other and accumulate over the life course [20]. The large heterogeneity in health status and circumstance observed in older adults is likely to strongly reflect the accumulated impact of these determinants [21,22], inextricably linking poorer *healthy ageing* trajectories to socioeconomic inequality.

Although maintaining and optimising IC across a person's life course has been suggested by the WHO as a means to reach healthy ageing, the contribution of cumulative health inequalities over time to changes of IC in late life has not been well researched. To fill the gap, this study aims to longitudinally examine the relationships between life-course factors and IC in a representative sample of China's older adult population. Additionally, we use a regression-based model to decompose the socioeconomic inequalities into life-course factors and their contribution to IC inequalities over time to further inform early-life policy and clinical interventions.

Methods

Data and Study Participants

We used de-identified data from the China Health and Retirement Longitudinal Study (CHARLS) to measure the IC construct and to examine life-course inequalities within it. The CHARLS aims to collect high-quality data from a nationally representative sample of older Chinese adults aged 45+ [23]. The design of the CHARLS is comparable to the US Health and Retirement Study and the English Longitudinal Study of Ageing. The first CHARLS cohort was recruited in 2011, with follow-up surveys conducted every two years. The 2011 nationally representative baseline sampling frame included 150 counties/districts and 450 villages/urban communities across China. All living respondents from the first two waves (2011 and 2013) were invited to also participate in the 2014 CHARLS Life History Survey, which included a series of questions about health and healthcare history, residential history, education history and important childhood events. The Biomedical Ethics Review Committee of Peking University approved the CHARLS study (IRB00001052–11015), and all the data is publicly available. Furthermore, the current study received approval from UNSW Ethics Committee (HC210472).

We included all individuals who participated in the 2011 and 2013 waves of CHARLS and the 2014 CHARLS Life History Survey. We only excluded individuals who did not answer IC questions ($n = 117$) and had missing information on life history ($n = 7{,}651$) or socioeconomic factors ($n = 941$). This produced a sample of 21,783 participants. Potential selection bias was appraised during our sensitivity analysis.

Intrinsic Capacity

We have described the validation of IC prognostic value in our previous analysis of the same cohort [15]. In summary, we calculated IC using structural equation models and confirmatory factor analysis of all objective characteristics that might be associated with the IC construct, including forced expiratory volume, chair-stand test, grip strength, balance, walking speed, haemoglobin, episodic memory test, affect, hearing and vision impairments, intact mental status, and sleep quantity and quality. The final construct includes one general factor (IC) and five subfactors: locomotor capacity, cognitive capacity, vitality, sensory capacity and psychological capacity [14,15] with a mean of 0 and a standard deviation of 1. Higher scores indicate a higher capacity to do the things individuals have reason to value and vice versa. This approach to measuring IC is consistent with a similar analysis of a large English cohort, suggesting it is robust across different cultural settings [15,24,25].

Life-course Factors

One of this study's aims is to estimate how early-life factors contribute to IC inequalities over time. Life-course analysis is now increasingly recognised in functional phenotype research. It conceptualises an accumulation of risk as the incremental burden of different exposures with age, highlighting the importance of timing and cumulative exposure [26]. These exposures may play a role via direct physiological change (i.e., weight loss due to famine), or through internal adjustment or modification (i.e., downregulation of the growth hormone insulin in relation to dietary exposure). Therefore, we included eleven early-life factors that happened in critical periods of individuals' lives based on the existing literature [27–30]: 1) parental education; 2) self-reported health status during childhood; 3) access to healthcare services; 4) healthy behaviour; 5) nutritional status; 6) childhood family economic status; 7) neighbourhood quality; 8) friendship with others; 9) parental mental health; 10) domestic violence; 11) receiving mentorship and support. More details are provided in *Supplement 1*.

Early-life factors may have a long-term impact on late-life IC directly or play a role via the cumulative effect on current socioeconomic position or a combination of both. Therefore, current socioeconomic position was used and measured in four dimensions, with family economic status considered the most important variable of interest. For this variable, we used annual per-capita household consumption expenditure, which is considered a better proxy for family economic status than family income because of the reluctance to report savings [27], and defined five groups using quantiles of per-capita household consumption expenditure (poorest, poorer, average, richer, richest). We also considered an individual's highest attained education level by creating a category variable (illiteracy, primary school, middle school, high school, college and above) [31] and included two binary variables: living in an urban area [28] and having an urban *hukou* [32]. Urban *hukou* was originally proposed as an internal passport permitting a person to live in an urban area in China and usually provides welfare and access to healthcare, housing and education [32].

Covariates

IC could also be influenced by demographic and lifestyle factors, and thus we included key demographic and lifestyle factors from the CHARLS data as covariates. For demographic factors, we included gender (male, female), age group (<45, [45–60), [60–70), [70–80), >=80) and marital status (married, other). For lifestyle factors, we included three binary variables, tobacco consumption, alcohol consumption in the past year, and the presence of any one of twelve chronic diseases. We also included province and wave fixed effects in the models. Robust standard errors were clustered at the household level.

Statistical Analysis

The present study aims to examine life-course inequalities in IC. First, we examined the unadjusted association of IC with each early-life, current socioeconomic, demographic and lifestyle factor in a bivariate analysis [33]. A multivariate analysis combining early-life factors and IC provided baseline results. Since there is a potential channel of early-life factors contributing to inequalities in IC via cumulative socioeconomic factors, the correlation between early-life factors and current socioeconomic position was examined using a Spearman correlation matrix [33].

Second, we used ordinary least square regression to examine how early-life factors and current socioeconomic factors were associated with IC, adjusting for demographic and lifestyle factors. Mediation analysis identified the direct and cumulative contribution of early-life factors. Associations were expressed as marginal effects (dy/dx) measured at the mean of each covariate. The estimated relationship between IC and the factors of interest can be biased due to endogeneity when the outcome variable and error term are correlated. In this case, our primary econometric strategy was to employ a 'mopping-up' approach [34], exploiting the comprehensive information in the CHARLS data to directly account for as many potential confounding factors as possible.

Third, we used the concentration index to measure inequalities in IC and its five subdomains [35]. The concentration index was calculated by family economic status because it is a rank-dependent method (*Supplement 1*). The standard concentration index is not necessarily invariant to arbitrary retransformations of a cardinal variable, and the problem was addressed using the modified concentration index (*Supplement 1*) [36,37]. The concentration index ranges from -1 to 1, with positive values indicating that persons with a higher IC are more concentrated among high-income groups (pro-rich inequalities) and vice versa. The larger the absolute value of the concentration index, the greater the IC inequality.

Fourth, we decomposed the concentration index of IC to quantify each determinant's specific contribution while controlling for other determinants (*Supplement 1*) [35]. Each factor's contribution to the concentration index was calculated separately and summarised by category. Additionally, by dropping socioeconomic factors from our models, we performed mediation analysis to identify the direct contribution of early-life factors to IC inequality and the cumulative contribution of socioeconomic inequalities over time.

Because a moderate proportion of participants was excluded, we used an incidental truncation model by introducing the inverse Mills ratio to adjust for potential selection bias [38]. We used multiple imputations with chained equations to impute missing values [39], assuming observations were missing at random. Estimates were combined across 20 imputed datasets based on Rubin's rules [40]. We also separated the whole population into a younger group (aged <60) and an older group (aged 60+) to perform heterogeneity analysis. We reported two-sided *p*-values (unadjusted for multiple comparisons) and 95% confidence intervals throughout this study. A p-value < 0.05 was considered to indicate statistical significance. All analyses were performed in Stata 16.0 (Stata Corp LLP, College Station, TX, USA).

Results

A total of 21,783 survey participants were included in our analysis, with a mean age of 59.07 years (SD 9.16). The sample included 9,997 participants in the older group (mean age: 67.15 years old; SD: 6.01) and 11,786 participants in the younger group (mean age: 52.22 years old; SD: 4.71). Among the included participants, 10,600 (48.66%) were male. Those excluded were more likely to have a lower socioeconomic position in family economic status, a lower education level and not having urban *hukou*. Also, the excluded participants were more likely to be older, single, female, more likely to consume tobacco and alcohol, and more likely to have chronic diseases (Table S1).

We first examined the relationship between IC and each life-course factor. We plotted Kernel density distributions to help form an intuition of association between IC and early-life factors (Figure 1). The plots showed that disadvantaged participants with lower parental education, worse childhood health, higher neighbourhood adversity and higher friendship deficiency had lower IC values than advantaged participants. The pattern held for other early-life factors as the bivariate analysis systematically associated early-life disadvantages with lower values of IC and its subfactors ($p < 0.001$) using the unadjusted models (Table S2). The multivariate analysis also supported these results (Table S3). Second, IC and its five subfactors (Table S4) were significantly associated with current socioeconomic, demographic and lifestyle factors ($p < 0.001$). Third, the Spearman correlation matrix for the correlation between early-life factors and current socioeconomic position showed reasonably moderate and strong correlations for factors across life-course stages (Figure 2).

The association between IC and life-course factors was further investigated using regression analysis. In general, early-life factors were significantly associated with IC over thirty years later, even after eliminating the effect of current socioeconomic, demographic and lifestyle factors (Figure 3 Panel A and Table S5). For example, persons with a literate father (or mother) recorded a 0.040 (95% CI: 0.020 to 0.051) (or 0.027 (95% CI: 0.009 to 0.044)) higher IC value than those with an illiterate father (or mother). Persons who did not have access to vaccines (or a physician) during childhood recorded a 0.027 (95% CI: 0.012 to 0.042) (or 0.030 (95% CI: 0.012 to 0.048)) lower IC value than those who did have access. Compared to persons who did not experience starvation during childhood, persons who experienced sustained starvation during childhood recorded significantly lower IC values (0.033 of a standard deviation, 95% CI: 0.016 to 0.050). Persons with average (or worse) self-reported health during childhood recorded a significant 0.043 (95% CI: 0.032 to 0.054) (or 0.082 (95% CI: 0.065 to 0.099)) lower IC value than persons with good health. Additionally, those with severe illness after the age of 16 recorded significantly lower IC values (0.064 of a standard deviation, 95% CI: 0.050 to 0.079). Persons who lived in adverse neighbourhoods and lacked friendships during childhood recorded significantly lower IC values; dose-response effects were also identified. A participant's father's (rather than mother's) mental health during childhood had a long-term negative effect on the participant's IC. Finally, receiving mentorship and support from others was significantly associated with higher IC values by 0.019 (95% CI: 0.007 to 0.031) of a standard deviation.

Apart from early-life factors, a higher current socioeconomic position was significantly associated with a higher IC value for participants with a higher family economic status, who lived in an urban area, had an urban *hukou* or had attained a higher level of education (Table S5). Additionally, we observed a dose-response effect on IC for family economic status and educational attainment level. Compared to participants in Quantile 1 for family economic status, participants in Quantiles 2–5 demonstrated 0.032 (95% CI: 0.017 to 0.047), 0.044 (95% CI: 0.029 to 0.059), 0.048 (95% CI: 0.032 to 0.063) and 0.066 (95% CI: 0.049 to 0.082) higher prognostic values, respectively. Meanwhile, compared to illiterate participants, participants who had completed primary school, middle school, high school, and college and above recorded 0.193 (95% CI: 0.178 to 0.208), 0.302 (95% CI: 0.285 to 0.320), 0.361 (95% CI: 0.339 to 0.382) and 0.412 (95% CI: 0.353 to 0.472) higher prognostic values.

Meanwhile, adverse childhood experiences were mainly associated with low values of cognitive and sensory capacities, although negative effects were also identified for locomotor, vitality and psychological capacity (Figure 3 Panel B-F and Table S5). As displayed, most estimated coefficients for cognitive and sensory capacities were statistically significant with narrower 95% confidence intervals (Figure 3 Panel B and C). For example, persons with a literate father recorded a 0.077 (95% CI: 0.057 to 0.096) higher cognitive capacity value than those with an illiterate father. Persons with a literate mother recorded a 0.040 (95% CI: 0.019 to 0.061) higher sensory capacity value than those with an illiterate mother. Compared to persons who did not experience starvation during childhood, persons who experienced sustained starvation during childhood recorded significantly lower cognitive capacity values (0.030 of a standard deviation, 95% CI: 0.000 to 0.059) and sensory capacity values (0.035 of a standard deviation, 95% CI: 0.015 to 0.054). However, most estimated coefficients for locomotor, vitality and psychological capacity were either not statistically significant or with wider 95% confidence intervals (Figure 3 Panel D-F), denoting statistically less precise estimations.

We performed two sensitivity analyses. First, we used the inverse Mills ratio to adjust for potential sample selection concerns due to missing values (Table S6); second, we used multiple imputations with chained equation to deal with missing data (Table S7). All these sensitivity analyses did not substantially change our results, which suggests that our results are robust without excluded participants.

Our mediation analysis excluded the current socioeconomic factors from regression models; therefore, the coefficients of early-life factors include their direct effects on IC and their cumulative effects on IC through current socioeconomic factors. According to these results, the marginal effect of early-life factors on IC generally became larger (Table S8), supporting the suggestion that early-life factors play a role in influencing late-life IC through the accumulation of socioeconomic inequalities.

The concentration index method enabled us to estimate the extent of inequalities in IC and identify the comparative importance of different factors using a regression-based decomposition. The concentration index was 0.024 (95% CI: 0.021 to 0.027) for IC, 0.002 (95% CI: -0.002 to 0.006) for locomotor, 0.043 (95% CI: 0.036 to 0.050) for cognitive capacity, 0.012 (95% CI: 0.011 to 0.013) for vitality, 0.032 (95% CI: 0.025 to 0.039) for sensory capacity and 0.005 (95% CI: -0.006 to 0.016) for psychological capacity. The positive values indicate the existence of pro-rich IC inequalities, that is, higher IC values are more concentrated among the rich. Notably, the absolute values for cognitive capacity and sensory capacity were larger than the concentration index for IC, indicating that IC inequality was driven by inequalities in cognitive and sensory capacity. Additionally, our subgroup analysis showed a concentration index of 0.019 (95% CI: 0.015 to 0.023) for IC for the younger group compared to 0.027 (95% CI: 0.022 to 0.032) for the older group, indicating greater inequality within the older group. This pattern holds in locomotor and cognitive capacity but not for vitality, sensory capacity and psychological capacity (Table S9).

We decomposed the concentration index into the contribution of each life-course factor (Table S10). Overall, early-life factors directly accounted for 13.92% (95% CI: 13.57% to 14.27%) of IC inequalities (Figure 4 Panel A); lifestyle factors, demographic factors, socioeconomic position (excluding family economic status) and family economic status accounted for -0.47% (95% CI: -1.20% to 0.26%), 8.49% (95% CI: 8.26% to 8.72%), 50.91% (95% CI: 43.96% to 57.86%) and 24.63% (95% CI: 19.02% to 30.24%), respectively. Each factor's contribution was similar across subdomains, with psychological capacity the only exception. Notably, the decomposition results for locomotor and psychological capacity were less precise since these two subfactors only had small absolute values of the concentration index. Theoretically, each determinant's contribution to the concentration index of IC could be attributed to the interaction between changes in the determinant's concentration index itself and the determinant's partial effect on IC. In our mediation analysis, the marginal effect of early-life factors on IC generally became larger, leading early-life factors to account for 28.57% (95% CI: 28.19% to 28.95%) of IC inequalities, 25.36% (95% CI: 20.01% to 30.71%) of locomotor capacity inequalities, 25.12% (95% CI: 24.72% to 25.52%) of cognitive capacity inequalities, 23.23% (95% CI: 23.13% to 23.33%) of vitality inequalities, 27.08% (95% CI: 26.68% to 27.48%) of sensory capacity inequalities and 72.43% (95% CI: 68.14% to 76.72%) of psychological capacity inequalities (Figure 4 Panel B and Table S11).

Discussion

Using a large representative sample of the older Chinese population, we found that unfavourable early-life factors were linked to lower late-life IC value over thirty years later, both directly and through the cumulative effects of socioeconomic inequities over a person's life course. Unfavourable early-life factors were more likely to decrease an individual's cognitive and sensory capacities than locomotor functioning, psychological capacity or homeostasis. As a consequence, significant inequalities in IC were observed across the population with a higher current socioeconomic position associated with better outcomes. These inequalities varied substantially across the various IC subfactors, with more inequalities found in cognitive and sensory capacities. Although a participant's current socioeconomic position accounted for most IC inequalities, we found that early-life factors directly explained a substantial share of IC inequalities.

To the best of our knowledge, this is the first comprehensive life-course analysis of the socioeconomic determinants of inequalities in intrinsic capacity, a more holistic and strengths-based construct of human ageing than approaches considering specific conditions [41]. Although a moderate proportion of our sample was excluded from our analysis, the sensitivity analyses indicated that our results were reliable and robust.

Our findings were consistent with previous research linking early-life factors to specific late-life health outcomes as we found a robust relationship between early-life factors and late-life IC values that remained statistically significant after controlling for a variety of demographic, lifestyle and current socioeconomic factors. For example, unfavourable socioeconomic position, sustained starvation, low parental education, poor health status and the absence of essential healthcare services in childhood have been found to increase the likelihood of being frail in old age [27,30,42]. Meanwhile, our findings significantly associated better childhood friendships, healthy behaviour and receiving mentorship and support from others in childhood with a higher prognostic IC value in later life. However, our analysis of the broad IC construct also allowed us to examine the variation of these associations across subdomains and the factors across the life course that may influence these.

We found that early-life factors were more likely to impair cognitive and sensory capacities compared with locomotor functioning, vitality and psychological capacity. This is of interest since, in western Europe, cognitive capacity appears to be improving among older people when compared to previous generations of people of the same age [43], although the mechanism for this is unclear. Cognitive capacity in older age may be influenced by cognitive development in early life [44], which may be associated with child brain structural alterations of the cerebral cortex [45]. Although exposure to stressors is protective in that they promote short-term adaptation, it can lead to a long-term dysregulation of allostasis that promote maladaptive wear and tear on the body and brain under chronically stressful conditions [46]. Emerging evidence in neuroscience suggests that childhood adversity alters trajectories of brain development and negatively damages brain structure, function and connectivity [47]. For example, childhood adversity reduces the volume of the hippocampus, the volume of anterior cingulate and ventromedial and dorsomedial cortices [48,49]; affects the development of key fibre tracts [50]; appears to alter the development of sensory systems that process and convey stressful experiences [51]. Many of the early life characteristics associated with cognitive inequalities in our analysis (for example, literacy of the father or starvation in childhood) provide obvious routes to support this. The main early life characteristics associated with poor sensory capacity concerned starvation and illness which physiologically may have impacted the development of hearing and vision.

The smaller negative effect of early-life disadvantages identified for locomotor functioning, vitality and psychological capacities is somewhat surprising. Psychological capacity was partly dominated by early life determinants although less influence was identified, suggesting the influence of childhood development on the ability to manage stressors. Our measure of psychological capacity was dominated by a depression score [52], which itself is heavily influenced by current life events and genetic predisposition [53]. While diminished locomotor capacity was also associated with adverse early life or life course exposures, the impact was less than for cognitive capacity. Locomotor capacity is influenced by many factors with conflicting associations with socioeconomic position [54]. Moreover, the dysregulation derived from stressors in childhood could be masked by the growth of organs since locomotion covers skeletal muscle physiology, cardiovascular system energy homeostasis, osteoarticular and neurophysiology [55]. Finally, vitality could be less likely to be affected because of a person's underlying resilience to challenges, vigour and stamina, and thus maintain homeostasis in the face of daily stressors [56] compared with cognitive and sensory capacities, which are two major channels connecting individuals to their environments.

Our findings also lent support to the biological weathering theory that ambient stress of disadvantaged exposures fosters biological wear and tear throughout the life course [57]. Specifically, prolonged exposure to socioeconomic disadvantage fosters an adverse physiological response that damages cells and induces oxidative stress [58] and provides highly salient cues of threat that trigger negative emotionality and a cascade of biological responses that, over time, cause wear and tear on physiological systems, increasing the risk for biological ageing [59].

We have identified significant socioeconomic inequalities in late-life IC, a fine-grained proxy for the overall health of older adults, with a higher socioeconomic position linked to a higher overall IC value. These findings are consistent with previous studies that have provided comprehensive evidence across countries concerning socioeconomic determinants of various health domains [60,61], including self-rated health, quality of life [62,63], functional limitations in daily life [27], anthropometric measures [35] and even mortality [64]. However, much of this research is inconclusive for both effect size and direction [65–67], and some findings present conflicting results, likely due to the confounding effects of environmental factors on health. Moreover, many of the health-related outcomes studied previously have either been subjective or limited to various components of what might be considered as an individual's health status [27,30,65–68]. The bulk of these analyses has also had difficulty teasing out the role of early life and life course socioeconomic influences.

Distressingly, we found that the negative effect of early-life disadvantages on cognitive and sensory capacities persisted and accumulated over thirty years as we estimated greater inequalities in the two subfactors compared with inequalities in locomotor, vitality and psychological capacities. In fact, durable exposure to concentrated disadvantages in adulthood may still damage the person's cognition [69], and lower socioeconomic position in late life is related to an acceleration of ageing across a broad range of functional abilities and phenotypes, including cognition, locomotion, sensory and psychological functioning [70]. These associations are underpinned by biological processes such as chronic allostatic load and sustained inflammation [71,72]. Among life course determinants, the impact of education was also much greater for cognitive capacity than for all the other capacities. Combined, these late-life inequalities would reinforce the lasting impacts of early life educational opportunities. There is also a large body of evidence linking sensory impairments with later life socioeconomic disadvantage in a self-reinforcing relationship [73]. In contrast, a sedentary occupation may have been associated with more advantaged participants in this cohort of the Chinese population [74], and occupations involving more manual activities or participation in strenuous activities in day-to-day life might have some protective influences on locomotor function [75], although this might not be true for the most strenuous of occupations.

Although a participant's current socioeconomic position accounted for most IC inequalities, we found that early-life factors explained a substantial share of IC inequalities directly over thirty years later and via the cumulative effects of socioeconomic inequalities. Almost all of the determinants of these disparities can be shaped by public policies across an individual's life course [3]. Decomposing IC inequalities into life-course factors may help identify key components of proactive early-life interventions that aim to preserve IC in older age [5] because enshrining equitable early-life opportunities influences people's capacity to make choices, contribute to society and receive support when needed [3]. Importantly, reducing inequalities in family economic status and education and closing the gaps between urban and rural residents and urban *hukou* and non-urban *hukou* holders may contribute significantly to reducing overall IC inequalities. This evidence provides support for the Chinese government's latest initiatives, including "*common prosperity*" and "*rural revitalisation*", designed to reduce rural-urban disparities and wealth inequalities.

One of the strengths of this analysis is that it employs a rich set of early-life factors and current socioeconomic factors to examine an innovative measure for healthy ageing in the context of the world's largest ageing population. Indeed, social determinants have been found to influence each other beyond their simultaneous effect on health, resulting from the complex interplay between physical environments and culturally mediated behaviours and psychological factors. However, there has been recognition that the effect of social determinants of health should be examined and understood from a complementary rather than exclusionary perspective [26]. Furthermore, we adopted the novel approach of examining the mediating pathways of early-life factors and IC through the cumulative effects of socioeconomic inequalities.

We acknowledge several limitations. First, we used individual recall data for early-life factors, making recall bias inevitable. Second, IC trajectories are important for tracking health status over a lifetime; however, this study could not distinguish whether IC variations were caused by higher/lower peaks or faster/slower declining speeds of IC. Accordingly, we will further examine the longitudinal nature of IC when new CHARLS data becomes available. Third, potential cohort effects may limit the generalisation of our findings. Analysing age-period-cohort effects is beyond the scope of the study and will be further explored in an analysis using the longitudinal variations in IC. Fourth, genetics were not included in the study; instead, we included a comprehensive and rich set of variables to try our best to 'mop-up' individual heterogeneity. Finally, the current socioeconomic factors included in this study preclude the interpretation of our results as causal relationships.

To conclude, using a large representative sample of the older Chinese population, we found that unfavourable early-life factors were linked with lower IC in late-life directly and through the cumulative inequalities over time. Unfavourable early-life factors were more likely to damage an individual's capacities connecting the environment than internal organism homeostasis. A substantial share of IC inequality was explained by early-life factors that could potentially be reshaped by early interventions. Further studies using the variations in higher/lower peaks or faster/slower declining speeds of IC are needed.

Data availability: Data described in this paper are available at the website of the China Health and Retirement Longitudinal Study (http://charls.pku.edu.cn/en/).

Code availability: The code scripts used in this analysis are available from the corresponding authors upon reasonable request.

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Declaration of Conflicts of Interests: We declare no competing interests.

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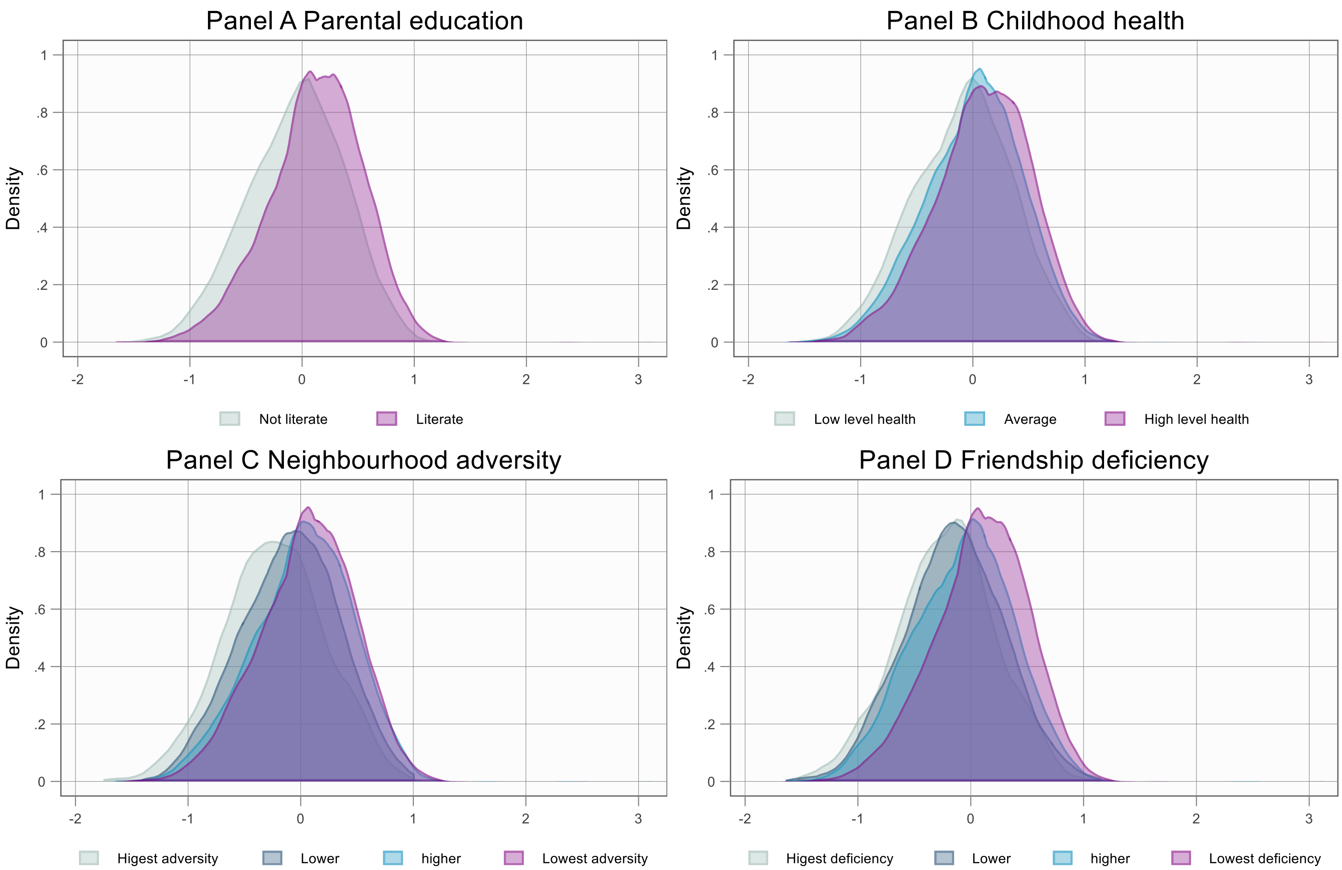


Figure 1 Kernel density of intrinsic capacity across parental education, childhood health, neighbourhood adversity and friendship deficiency ($N = 21{,}783$)

Note: Parental education was either mother or father of the participant being literate. The results were similar using other early-life factors and subfactors of IC. More details can be found in Table S2.

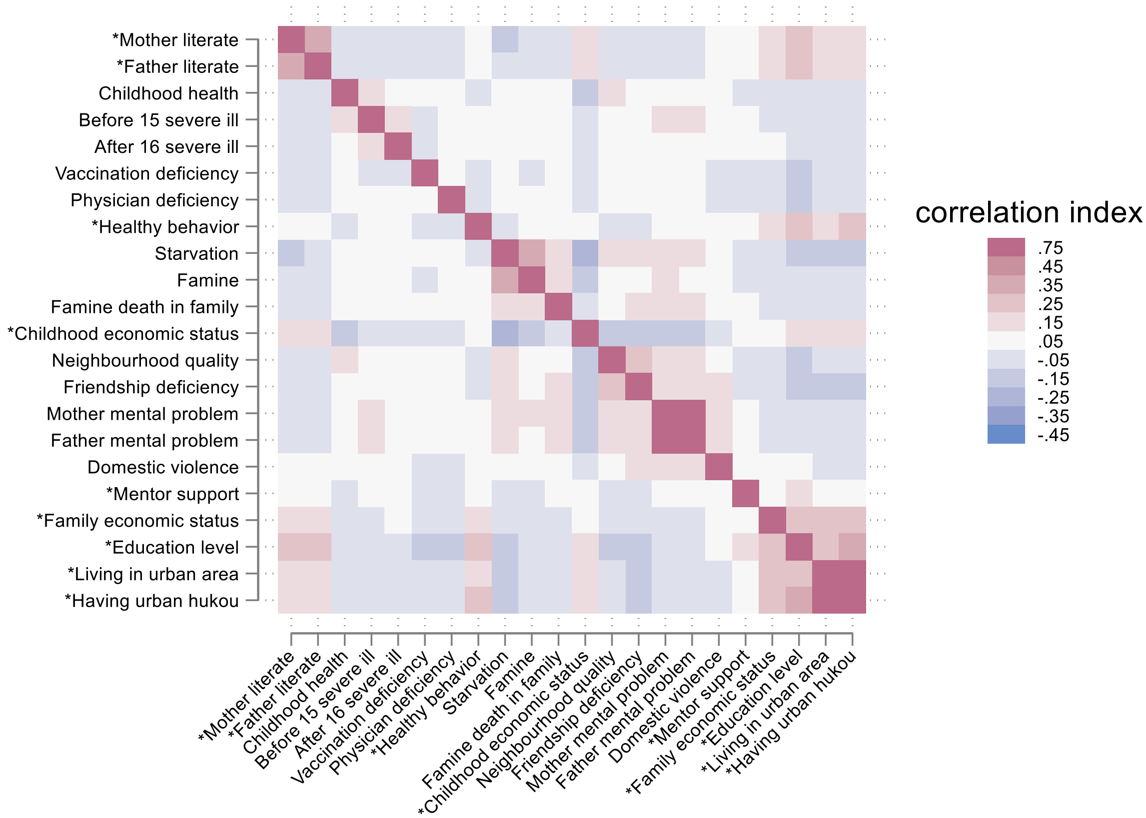
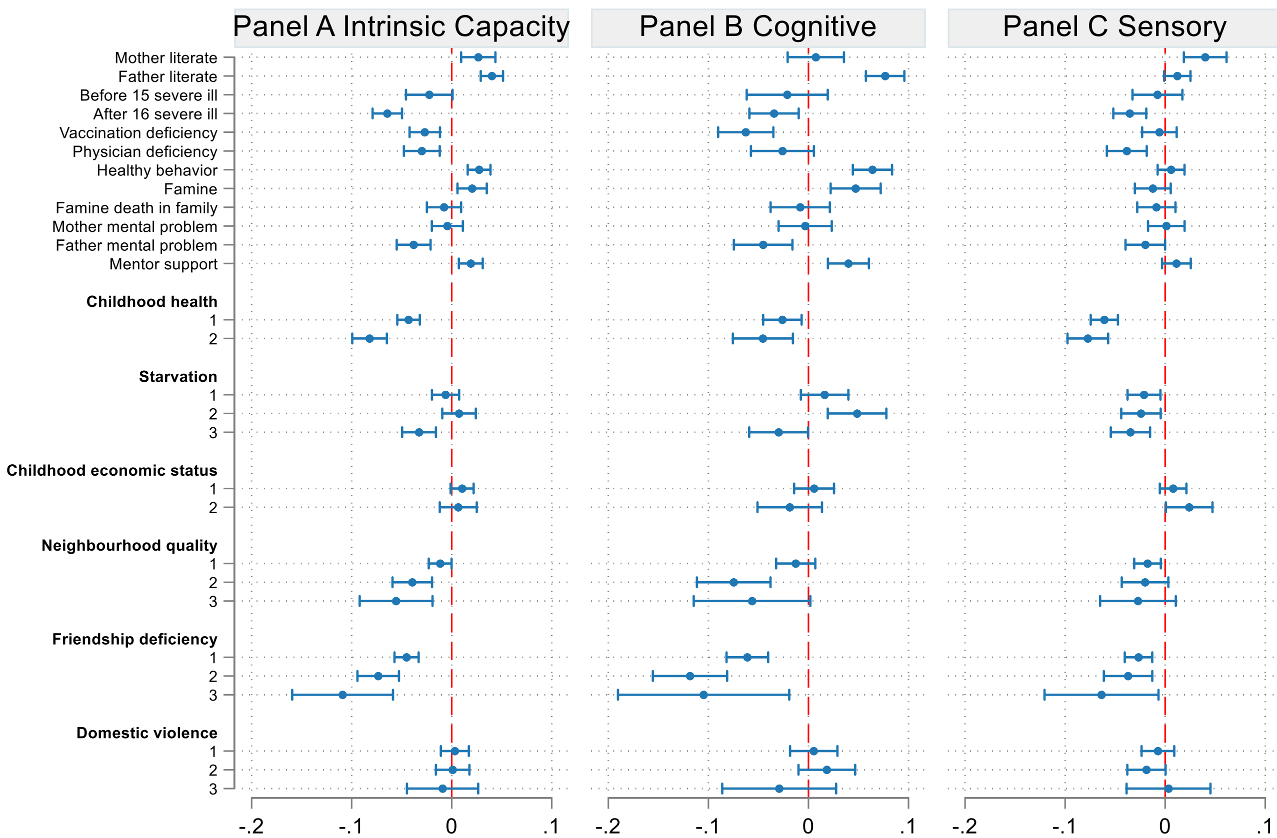


Figure 2 Pairwise Spearman correlation matrix between life course factors (N = 21, 783)

Note: * denotes positive measures with higher socioeconomic position or childhood advantages.


Panel A Intrinsic Capacity
Panel B Cognitive
Panel C Sensory
Mother literate
Father literate
Before 15 severe ill
After 16 severe ill
Vaccination deficiency
Physician deficiency
Healthy behavior
Famine
Famine death in family
Mother mental problem
Father mental problem
Mentor support
Childhood health
Starvation
Childhood economic status
Neighbourhood quality
Friendship deficiency
Domestic violence
-.2 -.1 0 .1

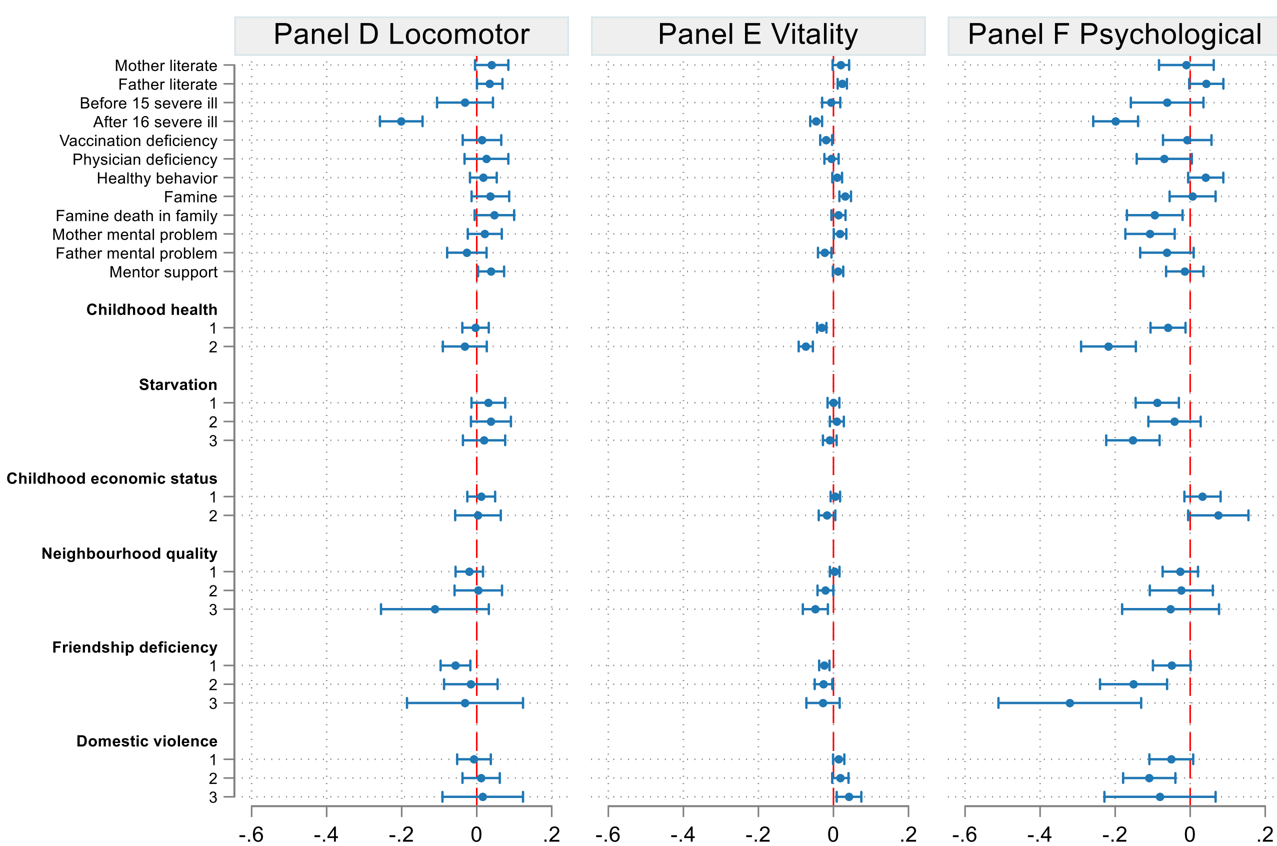

Panel D Locomotor
Panel E Vitality
Panel F Psychological
Mother literate
Father literate
Before 15 severe ill
After 16 severe ill
Vaccination deficiency
Physician deficiency
Healthy behavior
Famine
Famine death in family
Mother mental problem
Father mental problem
Mentor support
Childhood health
Starvation
Childhood economic status
Neighbourhood quality
Friendship deficiency
Domestic violence
-.6 -.4 -.2 0 .2

Figure 3 Linking early-life factors with late-life intrinsic capacity (*N* = 21, 783)

Note: Categorical variables were used ranging from 0 (lowest) to 3 (highest). Panel A-C and Panel D-F used different scales. Multivariate linear regressions were performed by adjusting for current socioeconomic factors, lifestyle factors and demographic factors; point estimations and 95% confidence intervals are shown. Locomotor mainly includes balance, muscle strength and gait; cognitive capacity includes memory, intelligence and problem-solving; vitality is defined as underlying a person's resilience to challenges, vigour and stamina, to maintain homeostasis in the face of daily stressors; sensory capacity includes vision and hearing; psychological capacity involves mood and emotional resilience. The details regarding coefficients can be found in Table S5.

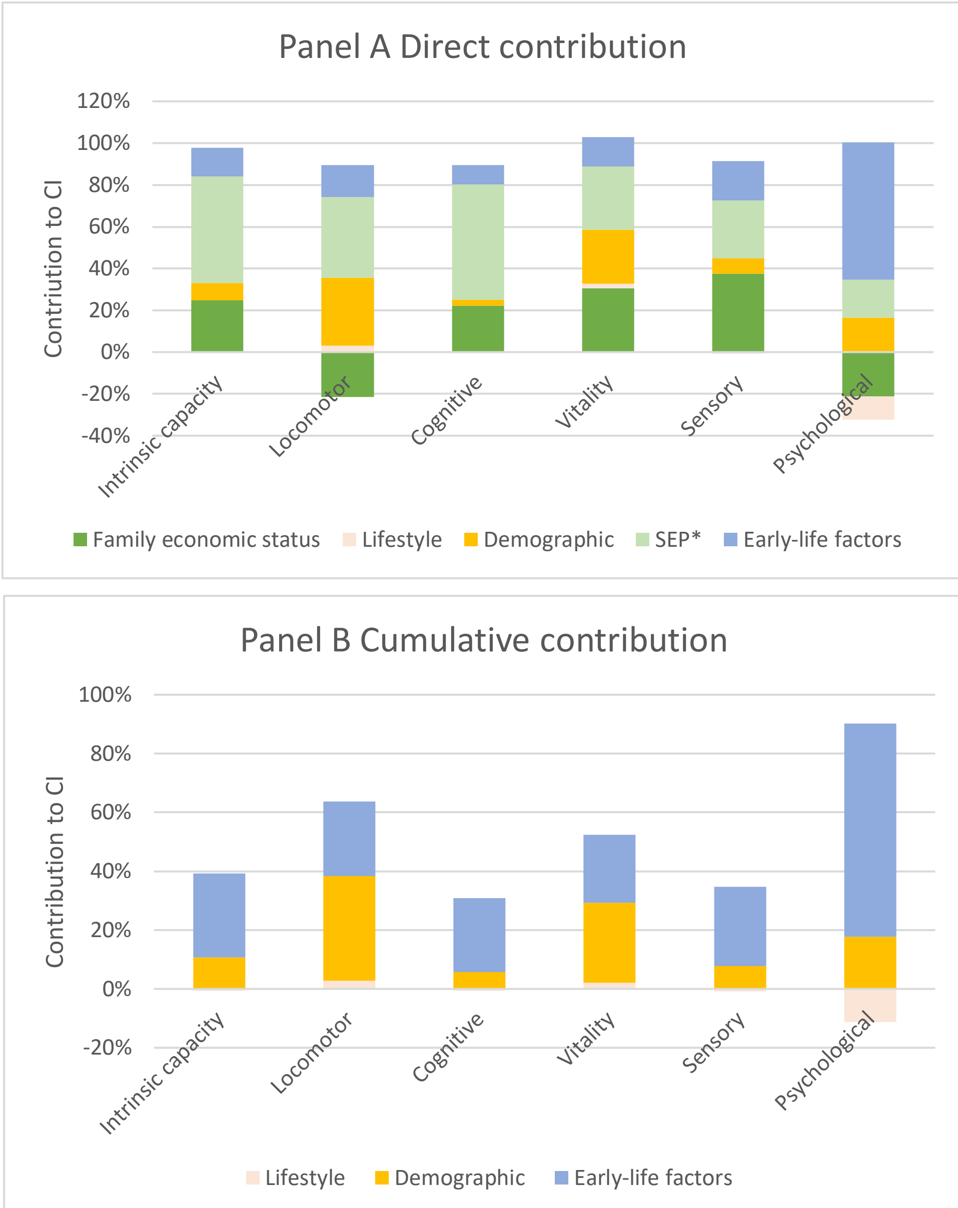


Figure 4 The contribution of each category to the inequalities in intrinsic capacity (N = 21, 783)

Note: The figure describes the percentage contribution of each category factor to the overall inequality in IC by decomposing the modified concentration index. In Panel A, all life course factors were included, and thus the graph shows the direct contribution of early-life factors to inequalities in IC. In Panel B, current socioeconomic position was excluded from the model of mediation analysis, and thus the graph shows the cumulative contribution of early-life factors to inequalities in IC. * Current socioeconomic position (SEP) excludes the family economic status factor.