**Title Page**

# Full Title: Is increased longevity leading to compression or expansion of morbidity? -- Evidence from cohorts of the oldest-old in China

**Brief Title: Is increased longevity leading to compressed or expansion of morbidity?**

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## Contributors

Y.Z. designed the study and drafted the paper; Q.S.F. performed the statistical data analysis and worked with Y.Z. to draft the paper. All authors discussed and contributed to the theoretical framework, interpretations of the results, revised and gave final approval of this manuscript.

## Conflicts of interest

We declare that we have no conflicts of interest.

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**Abstract**

**Background**. The oldest-old (≥80 years) are the most rapidly growing age group globally, and they most in need of health care and assistance. The aim of this study was to explore whether increased longevity is leading to populations of healthier oldest-old (compression of morbidity; benefits of success), or to less healthy and disabled oldest-elderly (expansion of morbidity, costs of success).

**Methods**. Data are from Chinese Longitudinal Healthy Longevity Study (CLHLS). Three pairs of cohorts aged 80-89, 90-99 and 100-105 (in total 19,528 oldest-old participants) were examined; the two cohorts in each pair were born ten years apart, with the same age at the time of the assessment in the CLHLS 1998 and 2008 surveys. Four health outcomes were investigated: annual death rate, self-reported Activities of Daily Living (ADL) disability, physical performance in three tests and cognitive function measured by Mini-Mental State Examination (MMSE).

**Findings**. Controlling for various confounding factors, compared to cohorts born 10-years earlier, annual death rates at oldest-old ages among later cohorts were all substantially reduced, and their ADL disabilities had significantly reduced; however, cognitive function and objective physical performance (stand-up from a chair, pick-up a book from floor, turning around $360^0$) were all significantly worse in later cohorts than earlier cohorts. We also found that mortality of female oldest-old was substantially lower, but their functional capacities in ADL, cognition and physical performance were worse, compared to their male counterparts.

**Interpretation**. These empirical findings can be explained by the theoretical framework of mixed effects of two opposing processes: advances in medications, lifestyle and socioeconomics may compress morbidity, that is, “benefits of success”, but lifespan extension may expand morbidity as more frail elderly survive with health problems, that is “costs of success”. Recent improvements in

living standards and availability of facilities for daily living among Chinese elderly may also contribute to the contrasting trends of ADL disability and physical performance.

**Research in context**

**Evidence before this study**. Existing literature has provided empirical support for "compression of morbidity" or "expansion of morbidity" in the process of human longevity increase, respectively. But none of them investigated the mixed effects of these two opposing trends in one single study with a large enough sample size of the oldest-old cohorts, except one study of Danish cohorts.

**Added value of this study**. Our findings support that, with increase of longevity (success), there are co-existence and mixed effects of "compression of morbidity (benefits of success)" and "expansion of morbidity (costs of success)", which is in general consistent with the Danish study which compared one pair of cohorts born 10 years apart and aged 93 or 95 in 1998 or 2010, with a total sample size of 5,430 nonagenarians. However, important differences are also observed. The novelty of present study is that we compare three groups of Chinese cohorts born 10 years apart and aged 80-89, 90-99 and 100-105, respectively, at the time of the surveys in 1998 or 2008, with a total sample of 19,528 oldest-old participants. The present study is the first investigation of this important issue based on the largest dataset of oldest-old cohorts in the world and from a developing country.

**Implications**. The combination of declining mortality with worsening cognition and physical performance among the rapidly growing oldest-old, has clear policy implications for health systems and for social care not only in China but also globally. There is an urgent need for many more state-subsidised public and private programmes and enterprises to provide services to meet the various needs of the rapidly growing elderly population. In addition, elderly chronic disease prevention programmes through individualised health interventions need to be prioritised.

## INTRODUCTION

Population aging is one of the major challenges facing most countries in the world, including China. The accompanied dramatic increase in numbers of oldest-old (aged over 80) is of particular concern, presenting a major challenge for health and social care systems, since the oldest-old often need daily assistance and medical care.[1] There is contention around two contrasting scenarios of health trends in aging populations. One view states that advances in medical technology, improvements in lifestyle and socioeconomic development will postpone the onset of disability and chronic diseases among the elderly, so that morbidity will be “compressed” in old age.[2-4] This is linked to the concept of “benefits of success” that is, people are living longer (success) and in better health at older ages than previously (benefits). In contrast, it is hypothesised that reduced mortality results in more frail elderly surviving with health problems, thus worsening the overall health of the elderly population. This is often referred to as expansion of morbidity,[5,6] closely linked to the concept “costs of success”, which specifically means that people’s lifespan is prolonging (success) but do so in worse health at older ages than previously (costs). It is argued that these two trends may coexist and interplay in reality,[7] and the concept of a "dynamic equilibrium” was introduced to understand the relation of morbidity and the life expectancy increases.[8]

Trends in the overall health status of the elderly are generally positive in high income societies.[9] There are also reports supporting the opposite trends in some major health indicators. For example, a study found that the objective function tests of physical capacity, lung function and cognition were significantly worse in 2002 compared to 1992 in a Swedish population aged over 77.[10] Although dementia incidence rates were reported to have declined in some European countries [11] and the United States,[12] nine large Japanese studies suggested that all-cause dementia and Alzheimer’s disease prevalence are increasing in Japan.[13] Building on the work of several studies, including two nationally representative surveys, opposing trends of improvement in disability measures, alongside an expansion of morbidity in chronic diseases and functional impairments were observed among Swedish oldest-old.[10,14]

Several studies have reported that the Activities of Daily Living (ADL) disability prevalence among Chinese elderly has decreased in the past two decades.[15-17] $$ However, Wu et al. concluded that dementia prevalence among elderly aged 70+ was in general increasing, based on an evaluation of seventy prevalence studies of dementia in Mainland China, Hong Kong and Taiwan from 1980 to 2012.[18] Similarly, Chan et al. found that the prevalence of all forms of dementia at ages 65-69 and 95-99 in China in 2010 increased 44·4% and 43·7%, respectively, compared to 1990.[19]

The existing literature has provided empirical support for "compression of morbidity" or "expansion of morbidity", respectively, but none of them investigated the mixed effects of these two opposing trends in one single study with a large enough sample size of the oldest-old. The exception is a Danish study of a cohort born in 1905 and assessed at age 93 in 1998, and compared with a later cohort born in 1915 and assessed at age 95 in 2010.[20] This study provided some support for the mixed effects of both "compression of morbidity" and "expansion of morbidity". But it is unclear whether these mixed effects also exist among the oldest-old in developing countries such as China. This study addresses this research question by conducting comparative analysis on cohorts of the oldest-old born in 1909-1918 vs 1919-1928 (aged 80-89 in 1998 vs. 2008), born in 1899-1908 vs 1909-1918 (aged 90-99 in 1998 vs. 2008), and born in 1893-1898 vs 1903-1908 (aged 100-105 in 1998 vs. 2008). To our knowledge, this is the first study on this important issue from a developing country. It uses the largest datasets of oldest-old cohorts in the world.

## METHODS

### Study population and assessment procedure

This study draws on data from 19,528 oldest-old participants aged 80-105 (including 7,288 octogenarians, 7,234 nonagenarians and 5,006 centenarians interviewed in 1998 and 2008) from the 1998 and 2008 waves of the Chinese Longitudinal Healthy Longevity Surveys (CLHLS). CLHLS is a nationwide survey conducted in a randomly selected half of the counties and cities in 22 of the 31 provinces, covering about 85 percent of the total population of China. The CLHLS tried to interview all centenarians who voluntarily agreed to participate in the study in the sampled counties and cities. The CLHLS also adopted a targeted random-sample design to ensure representativeness, through interviewing approximately equal male and female nonagenarians, octogenarians and young-old living “nearby” the centenarians, aimed to investigate determinants of healthy longevity of different and comparable age and gender groups, who live in the same social and natural environment The CLHLS was initially designed to facilitate international comparative analyses, and its questionnaire was translated from the instruments of the Danish longevity survey analysed by Christensen et al.[20] The instruments were adapted to the Chinese culture and socioeconomic context. A wide variety of international and domestic studies have confirmed that age reporting of the Han Chinese oldest-old is in general reasonably accurate, due to the cultural tradition of memorising one’s date of birth to determine dates of important life events such as engagement and marriage.[21,22]

The CLHLS 1998 and 2008 surveys used almost exactly the same ascertainment and assessment protocols. No proxy was used for the objective questions such as cognitive function and physical performance assessments. The survey was administered in the participants’ homes by well-trained interviewers from the local centres for disease prevention and control (CDC), aging committees or university students. More details about CLHLS data source, including sampling design, follow-up interviews with surviving participants and deceased participants' close family members, data quality and scales of the variables analyzed in this article, are described in the online Appendix.

## Statistical analyses

We compared annual death rates, self-reported ADL disability, physical performance in three tests and cognitive function measured by MMSE scores for men and women separately and for both sexes combined. We did the standard statistical $\chi^2$ tests (one-sided) or z tests (two-sided) for categorical data, and t tests (two-sided) for continuous data. We also conducted multivariate regression analyses to explore the changes in mortality, physical and cognitive functions between the oldest-old cohorts born 10 years apart, adjusted for the covariates of age, rural/urban residence, marital status and education, which are the major demographic and socioeconomic factors affecting the elderly mortality and health in China. The mortality analysis is based on parametric survival models with Weibull distribution, as the Weibull assumption was satisfied and it has the best model fit.  All other analyses are based on logistic regression models or linear regression models. STATA 13.1 was used to perform the statistical analyses.

## RESULTS

Table A1 of the Appendix presents the comparisons of the basic demographic characteristics of the cohorts. Tables 1-3 present the detailed results of cross-cohort changes in physical and cognitive functions and follow-up death rates of oldest-old men, women and two genders combined. Figures 1-3 and Table 4 present the summary results. Our main findings can be summarized as a few key points as follows.

(1) The age-sex-specific death rates among Chinese oldest-old aged 80-89, 90-99 and 100-105 were all reduced in the later cohorts, compared to the cohorts born 10 years earlier (Figure 1; Tables 1-3). All of the nine sets of comparisons of age-specific death rates between different cohorts of the oldest-old showed follow-up mortality reduction in the range of annual rates of -0·2% to -1·3%. Adjusted for covariates of age, gender, education, rural/urban residence, the cross-cohort reduction in age-sex-specific mortality rates were statistically significant ($p<0·01$) in gender-combined centenarians and $p<0·05$ in female centenarians; marginally significant with $p<0·1$ in gender-combined octogenarians and nonagenarians, male octogenarians, and male centenarians; and not statistically significant in female octogenarians, and male or female nonagenarians (Tables 4).

(2) The ADL disability of the Chinese oldest-old was significantly reduced in the later cohorts, compared to the earlier cohorts (Figure 1; Tables 1-3). All of the nine sets of comparisons between different cohorts of the oldest-old showed substantial reduction in ADL disability in the range of annual rates of -0·8% to -2·8% (Table 4). Adjusted for the covariates, the cross-cohort reductions in ADL disability were statistically significant ($p<0·001$) in genders-combined nonagenarians and centenarians, and female centenarians; significant with $p<0·01$ in gender-combined octogenarians, male or female nonagenarians, male centenarians; significant with $p<0·05$ in female octogenarians; and marginally significant in male octogenarians (Table 4).

(3) The objective physical performance test scores of standing-up from a chair, picking-up a book from the floor and turning-around $360^0$ among the Chinese oldest-old were all significantly worsened in the later cohorts, compared to the earlier cohorts (Figure 2; Tables 1-3). All of the twenty-seven sets of the comparisons of physical performance tests scores between different cohorts of the oldest-old showed substantial reduction in the range of annual rates of -0·4% to

-3·8% (Table 4). Adjusted for the covariates, the cross-cohort differences in the objective physical performance test scores were highly significant in male, female and genders-combined octogenarians, nonagenarians and centenarians, with $p<0·001$ in 24 comparisons, $p<0·01$ in two comparisons and $p<0·05$ in one comparison (Table 4).

(4) The cognitive function measured by the MMSE test scores of the Chinese oldest-old was significantly worse in the later cohorts, compared to the earlier cohorts (Figure 2; Tables 1-3). All of the nine sets of the comparisons of cognitive function between different cohorts of the oldest-old showed significant reductions in the range of annual rates of -0·7% to -2·2% (Table 4). Adjusted for the covariates, the cross-cohort differences in cognitive functional scores were statistically significant with $p<0·001$ in all of the nine comparisons for male, female and genders-combined octogenarians, nonagenarians and centenarians (Tables 4).

(5) Comparisons of the six pairs of male-female oldest-old cohorts aged 80-89, 90-99 and 100-105 in 1998 and 2008 presented in the last 2 columns of Tables 1-3, consistently demonstrated that male oldest-old had substantially higher age-specific death rates, but substantially better health status in ADL disability, physical performance tests scores and cognitive function. The gender differences in the 48 male-female comparisons were statistically significant ($p<0·05$; mostly $p<0·001$), except three were marginally significant ($p<0·1$) in octogenarians and centenarians and three were not significant in octogenarians.

(6) Comparisons of the pairs of oldest-old cohorts aged 80-89, 90-99 and 100-105 in 1998 and 2008 presented in online Appendix Figure A1, indicated that the average proportions of self-reported life satisfaction and self-reported good health significantly declined among the later oldest-old cohorts compared to the earlier oldest-old cohorts ($p<0·001$), except self-reported health in the

centenarians (p=0·255). It is interesting to note that the period cross-sectional comparisons showed that average proportions of self-reported life satisfaction and self-reported health slightly increase or remain almost the same from ages 80-89 to 90-99 and 100+ either in 1998 or 2008 (online Appendix Figure A1), while the disabilities measured by the scores of ADL, cognitive function and physical performance were all largely increased with increase in ages (Figures 1-2).

## DISCUSSION

We compared three groups of Chinese cohorts born 10 years apart and aged 80-89, 90-99 and 100-105, respectively, at the time of surveys in 1998 or 2008. Our study is in general consistent with the Danish study which compared one pair of cohorts born 10 years apart and aged 93 or 95 at the time of the surveys in 1998 or 2010.[20] But we also observed important differences.

Both our Chinese study and the Danish study found that death rates and disability in activities of daily living among the later cohorts of the oldest-old were substantially reduced, compared to the cohorts born 10 years earlier. However, the test scores of objective physical performance (stand-up from a chair, pick-up a book from the floor, and turning around $360^0$) of the Chinese oldest-old were all significantly worse in the later cohorts, compared to the earlier cohorts. This is mostly consistent with the general pattern in the Danish study. Compared to the earlier cohort, the Danish later cohort had substantially worse ability to stand-up from a chair, significantly lower ability to walk for three meters among females and for both sexes combined.[20]

Both the present study and the Danish study report apparently contradictory findings with respect to survival and self-reported ADL disability versus objective physical performance tests. We believe that two underlying factors may help to understand this phenomenon. The first is the mixed effects of the two opposing processes of the "compression of morbidity (benefits of success)" and "expansion of morbidity (costs of success)". On one hand, the later cohorts might benefit from progress resulted from more effective disease treatment, healthier lifestyles, declining disability effects of some major chronic diseases such as stroke and cardio-metabolic disease,[16] and improved standards of living, due to rapid socioeconomic development in China. This "benefits of success" implied that the later oldest-old cohort experienced reduced mortality rates by postponement of senescence, and reached older ages with improved health and functional capacity in daily living.[4] On the other hand, as compared to the earlier cohort, the later cohort includes more members who have survived life-threatening conditions (because of improvements in medical care and increased longevity), but they might be in relatively poor health, namely, saving lives might reduce overall physical functional capacity and health.[20] As discussed in the Introduction section, we propose to use the term "costs of success" to describe this phenomenon.

The second underlying factor is associated with different types of disability measurements. The self-reported ADL disability depends not only on health status, but also on facilities to assist the activities of daily living, such as transferring, using the toilet, and bathing. The substantial improvement of ADL among the Chinese oldest-old could be partly due to the rapid changes in living standards and availability of facilities for daily life over the past couple of decades in China. For example, the average annual disposable income among urban and rural households in 2008 were 3·0 and 2·2 times as high as that in 1998, respectively.[23] Such rapid improvements in living standards which provide better facilities for daily life could help to explain the significant decreases in ADL disability. But the objective physical performance tests do not depend on facilities. Furthermore, self-reported ADL is subject to substantially higher measurement errors, compared to the objectively-tested cognitive function and physical performance scores.[24] Thus, self-reported ADL disability scores may not be considered as an accurate indicator of physical health status, while it can be used as a good measurement of assistance needs in daily living activities. The objective physical performance tests have added predictive value beyond the self-reported measures of disability, in evaluating actual health status changes, and in making decisions about health interventions.[25]

Cognitive function among the Chinese oldest-old was substantially and significantly worse in the later oldest-old cohorts, compared to the earlier cohorts, which is consistent with the trends found in the other studies in Mainland China, Hong Kong and Taiwan.[18,19] However, the Danish 1915 cohort scored significantly better on the MMSE than did the 1905 cohort.[20] We believe the explanation for this disparity lies in cross-cohort differences in education. For the two sexes combined, the weighted average education levels of the three Chinese later cohorts born in 1903-1908, 1909-1918 or 1919-1928 were significantly lower than that of the three corresponding cohorts born 10 years earlier (p=0·026~p<0·001), adjusted for age, gender, rural/urban residence and marital status. The retrospectively self-reported weighted average proportion of frequently going to bed hungry as a child among the later cohorts were 30·5% higher than that in the earlier cohorts. Such cross-cohort differentials in educational attainments and childhood conditions were due to more domestic wars during the periods when the later cohorts were children, compared to the earlier cohorts. This implied that the poorer education, childhood conditions and subsequent adult socioeconomic status experienced by the later cohorts contributed to their lower cognitive function score, as shown in other publications using the CLHLS data.[26] This is in addition to the “costs of success” effects which “saved” some frail elders from dying, but rather surviving with poor cognitive function. However, the Danish 1915 cohort’s average education level was significantly better than the 1905 cohort (p=0·006). Because higher education level is strongly associated with better cognitive function in old ages,[27] the positive effects of higher education level in the Danish later cohort might surpass the negative effects of “costs of success” on cognitive function.

We observed that the magnitude of the difference in physical and cognitive functions between the later and earlier oldest-old cohorts is substantially larger in the Chinese compared to the Danish. For example, the annual rates of changes in the scores of ADL disability between the Chinese nonagenarian later and earlier cohorts were 2.3%, in contrast to 1.1% in the Danish nonagenarian cohorts. Such Chinese-Danish differentials in magnitude of the cohort changes are understandable, because China is still undergoing rapid health transition and socioeconomic development, while Denmark has passed such a stage a few decades ago.

It is understandable that the average proportion of self-reported life satisfaction and self-reported good health substantially declined among the Chinese later oldest-old cohorts compared to the earlier cohorts (online Appendix Figure A1), as the later cohorts had significantly worse scores of physical performance and cognitive function, while their expectancy of good life and health was higher with increase of living standard. In line with the Chinese results, the opposite trend was observed in the Danish cohorts where the fraction of individuals with excellent self-reported health increased substantially (unpublished data).

The period cross-sectional comparisons showed that the disabilities measured by the scores of ADL, physical performance and cognitive function increased largely from ages 80-89 to 100+, however, the percent self-reporting satisfaction and good health slightly increased or remained almost unchanged from age 80-89 to 100+ (online Appendix Figure A1). This finding is consistent with the research on optimism and survival in the Danish 1905 cohort,[28] and the three Danish population-based surveys (including 11,307 participants aged 45+ years, of whom 2,411 were in the age group of 90+) which demonstrated that decline in ADL and cognitive function does not necessarily affect happiness in older ages.[29] Our Chinese and the Danish findings may suggest that being more positive in one's outlook on life, i.e. optimism and happiness, increases the chance of longevity.

Populations in China and many other countries in the world are aging rapidly.  The oldest-old will increase much faster than any other age groups. The findings of the present study and other recent research,[10, 13,14, 18-20, 30] provides a clear warning message to the al aging populations, namely, while human beings enjoy increase in longevity and improvement in some health indicators (benefits of success), other major health indicators may get worse (costs of success). This poses enormous challenges for the health system, social care and families, not only in China but also globally, especially in other developing countries. This calls for policy actions. Thus, we believe that, to fully harvest the benefits of and reduce the costs of the success from increasing lifespan, it is crucially important to develop many more state-subsidised public and private programmes and enterprises to provide services to meet the various needs of the growing elderly populations of both oldest-old and young-old in China and globally. These should include long-term and acute daily care and mobility aids for the disabled, working opportunities for those elders who are still active, service and individualized intervention programmes for social and leisure activities, continued learning, opportunities for tourism, psychological counselling, and remarriage bridge-building.

The present study has also important limitations and further research is needed. For example, additional in-depth studies are warranted to develop a deeper understanding of the mechanisms and causalities of how and why the mortality risk and ADL disability significantly declined due to "benefits of success", while the objective physical performance test and cognitive functional scores were significantly reduced due to the effects of "costs of success". The present study did not investigate the trends of changes in prevalence of clinically diagnosed chronic diseases between the earlier and later oldest-old cohorts, and we did not make comparisons for the representative samples of young-old cohorts born 10 years apart, due to data limitation (sections A3 and A4 of online Appendix). Further studies need to extend the present analysis on oldest-old to cover all elderly age groups, and also include chronic diseases to fully understand the process of healthy aging in a life course perspective, with a sufficiently large sample size of both oldest-old and young-old cohorts. In-depth research on the trends between various health outcome indicators may provide solid evidence for health intervention programmes aimed at strengthening the positive effects of “benefits of success” and reducing the negative effects of “costs of success”. This would fundamentally contribute to the sustainable developments of human societies in the face of worldwide rapid population aging with increased longevity.

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Table 1· Differentials in mortality, cognitive and physical functions between cohorts born in 1909-1918 (aged 80-89 in 1998) and born in 1919-1928 (aged 80-89 in 2008)

| | **Two sexes combined** | | | | **Men** | | | | **Women** | | | | **Sex diffe** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Years of birth | | p-value of changes | | Years of birth | | p-value of changes | | Years of birth | | p-value of changes | | p-value (ad | |
| | 1909-1918 (n=3235) | 1919-1928 (n=4053) | Unadjusted | Adjusted¶ | 1909-1918 (n=1641) | 1919-1928 (n=2030) | Unadjusted | Adjusted¶ | 1909-1918 (n=1594) | 1919-1928 (n=2023) | Unadjusted | Adjusted¶ | 1909-1918 (n=3235) | 1 |
| e (standard division) | 83·07 (2·59) | 82·98 (2·57) | 0·1516* | 0·249 | 82·87 (2·51) | 82·81 (2·50) | 0·4955* | 0·328 | 83·20 (2·64) | 83·11 (2·61) | 0·3055* | 0·580 | | |
| **ual death rate** | 10·3% | 9·6% | 0·3204‡ | 0·060 | 12·5% | 10·9% | 0·1325‡ | 0·067 | 9·0% | 8·7% | 0·7523‡ | 0·264 | <0·001 | |
| **disability score** | | | | | | | | | | | | | | |
| an (range=0-6) | 0·36 (1·06) | 0·28 (1·01) | 0·0006* | 0·002 | 0·32 (1·01) | 0·24 (0·93) | 0·0219* | 0·029 | 0·39 (1·08) | 0·30 (1·06) | 0·0163* | 0·026 | 0·012 | |
| issing, n (%) | 18 (0·6%) | 1 (0·0%) | | | 10 (0·6%) | 1 (0·0%) | | | 8 (0·5%) | 0 (0·0%) | | | | |
| ped results, n (%) | | | 0·0015‡ | 0·005 | | | 0·2077‡ | 0·071 | | | 0·0055‡ | 0·029 | 0·042 | |
| 0-1 | 2974 (92·4%) | 3823 (94·4%) | | | 1525 (93·5%) | 1927 (95·0%) | | | 1456 (91·8%) | 1899 (93·9%) | | | | |
| 2 | 80 (2·5%) | 51 (1·3%) | | | 33 (2·0%) | 28 (1·4%) | | | 44 (2·8%) | 23 (1·2%) | | | | |
| ≥3 | 164 (5·1%) | 178 (4·4%) | | | 73 (4·5%) | 73 (3·6%) | | | 86 (5·5%) | 100 (5·0%) | | | | |
| **performance score** | | | | | | | | | | | | | | |
| d-up from chair | | | | | | | | | | | | | | |
| an (range= 0-1) | 0·92 (0·21) | 0·86 (0·28) | <0·0001* | <0·001 | 0·93 (0·20) | 0·87 (0·26) | <0·0001* | <0·001 | 0·92 (0·22) | 0·84 (0·29) | <0·0001* | <0·001 | 0·154 | |
| issing, n (%) | 15 (0·5%) | 1 (0·0%) | | | 9 (0·6%) | 0 (0·0%) | | | 6 (0·4%) | 1 (0·1%) | | | | |
| a book from floor | | | | | | | | | | | | | | |
| an (range= 0-1) | 0·90 (0·25) | 0·85 (0·29) | <0·0001* | <0·001 | 0·91 (0·23) | 0·87 (0·27) | <0·0001* | <0·001 | 0·89 (0·26) | 0·84 (0·29) | <0·0001* | <0·001 | 0·048 | |
| issing, n (%) | 18 (0·6%) | 0 (0·0%) | | | 14 (0·8%) | 0 (0·0%) | | | 6 (0·4%) | 0 (0·0%) | | | | |
| n-around $360^0$ | | | | | | | | | | | | | | |
| an (range= 0-1) | 0·91 (0·28) | 0·81 (0·39) | <0·0001* | <0·001 | 0·92 (0·27) | 0·84 (0·37) | <0·0001* | <0·001 | 0·91 (0·29) | 0·79 (0·41) | <0·0001* | <0·001 | 0·928 | |
| issing, n (%) | 11 (0·3%) | 1 (0·0%) | | | 10 (0·6%) | 0 (0·0%) | | | 2 (0·1%) | 1 (0·0%) | | | | |
| **MSE score** | | | | | | | | | | | | | | |
| an (range=0-30) | 24·82 (5·37) | 22·87 (7·27) | <0·0001* | <0·001 | 25·86 (5·09) | 24·18 (6·32) | <0·0001* | <0·001 | 24·17 (5·44) | 21·93 (7·56) | <0·0001* | <0·001 | <0·001 | |
| issing, n (%) | 26 (0·8%) | 9 (0·2%) | | | 13 (0·8%) | 4 (0·2%) | | | 12 (0·8%) | 5 (0·3%) | | | | |
| ped results, n (%) | | | <0·0001‡ | <0·001 | | | <0·0001‡ | <0·001 | | | <0·0001‡ | <0·001 | <0·001 | |
| 0-17 | 285 (8·9%) | 658 (16·3%) | | | 97 (6·0%) | 206 (10·2%) | | | 169 (10·7%) | 416 (20·7%) | | | | |
| 18-22 | 437 (13·6%) | 744 (18·4%) | | | 148 (9·1%) | 308 (15·2%) | | | 260 (16·4%) | 418 (20·7%) | | | | |
| 23-27 | 1328(41·4%) | 1439 (35·6%) | | | 642 (39·5%) | 791 (39·0%) | | | 674 (42·6%) | 668 (33·2%) | | | | |
| 28-30 | 1157(36·1%) | 1200 (29·7%) | | | 737 (45·4%) | 722 (35·6%) | | | 479 (30·3%) | 513 (25·5%) | | | | |

Notes: (1) The results are weighted averages using the age-sex-rural/urban-specific sample weights as described in section A1 of online Appendix; (2) *Test of equal mean; ‡Test of equal proportions; (3) ¶ Multivariate model test of the difference between the cohorts, adjusted for age, education, rural/urban residence, and marital status; for the two-sex combined, the gender was also adjusted for· The tests for annual death rates are based on parametric survival model with Weibull distribution; all other tests are based on logistic regression models or linear regression models·

Table 2· Differentials in mortality, cognitive and physical functions between cohorts born in 1899-1908 (aged 90-99 in 1998) and born in 1909-1918 (aged 90-99 in 2008)

| | **Two sexes combined** | | | | **Men** | | | | **Women** | | | | **Sex diffe** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Years of birth | | p-value of changes | | Years of birth | | p-value | | Years of birth | | p-value of changes | | p-value (ad | |
| | 1899-1908 (n=2896) | 1909-1918 (n=4338) | Unadjusted | Adjusted¶ | 1899-1908 (n=1243) | 1909-1918 (n=1810) | Unadjusted | Adjusted¶ | 1899-1908 (n=1653) | 1909-1918 (n=2528) | Unadjusted | Adjusted¶ | 1899-1908 (n=2896) | 1 ( |
| e (standard division) | 92·11 (2·13) | 92·24 (2·19) | 0·0109* | 0·020 | 92·00 (2·11) | 91·99 (1·99) | 0·9104* | 0·829 | 92·15 (2·14) | 92·33 (2·25) | 0·0078* | 0·007 | | |
| **ual death rate** | 24·1% | 23·4% | 0·4926‡ | 0·065 | 27·1% | 25·6% | 0·3545‡ | 0·118 | 23·0% | 22·6% | 0·7629‡ | 0·186 | 0·001 | |
| **disability score** | | | | | | | | | | | | | | |
| an (range=0-6) | 0·94 (1·62) | 0·74 (1·55) | <0·0001* | <0·001 | 0·74 (1·49) | 0·59 (1·42) | 0·0054* | 0·008 | 1·02 (1·66) | 0·80 (1·59) | <0·0001* | <0·001 | 0·002 | |
| issing, n (%) | 10 (0·3%) | 0 (0·0%) | | | 5 (0·4%) | 0 (0·0%) | | | 5 (0·3%) | 0 (0·0%) | | | | |
| ped results, n (%) | | | 0·0023‡ | <0·001 | | | 0·0238‡ | 0·008 | | | 0·0236‡ | 0·002 | 0·015 | |
| 0-1 | 2290 (79·4%) | 3618 (83·4%) | | | 1031 (83·3%) | 1578(87·2%) | | | 1283(77·9%) | 2073(82·0%) | | | | |
| 2 | 152 (5·3%) | 181 (4·2%) | | | 59 (4·8%) | 57 (3·2%) | | | 90 (5·5%) | 115 (4·6%) | | | | |
| ≥3 | 443 (15·4%) | 538 (12·4%) | | | 148 (11·9%) | 175 (9·7%) | | | 275 (16·7%) | 340 (13·5%) | | | | |
| **performance score** | | | | | | | | | | | | | | |
| d-up from chair | | | | | | | | | | | | | | |
| an (range= 0-1) | 0·80 (0·31) | 0·72 (0·34) | <0·0001* | <0·001 | 0·84 (0·28) | 0·77 (0·32) | <0·0001* | <0·001 | 0·78 (0·32) | 0·71 (0·34) | <0·0001* | <0·001 | <0·001 | |
| issing, n (%) | 24 (0·8%) | 10 (0·2%) | | | 10 (0·8%) | 7 (0·4%) | | | 14 (0·8%) | 4 (0·2%) | | | | |
| a book from floor | | | | | | | | | | | | | | |
| an (range= 0-1) | 0·77 (0·33) | 0·67 (0·37) | <0·0001* | <0·001 | 0·83 (0·30) | 0·74 (0·35) | <0·0001* | <0·001 | 0·75 (0·34) | 0·65 (0·38) | <0·0001* | <0·001 | <0·001 | |
| issing, n (%) | 28 (1·0%) | 3 (0·1%) | | | 13 (1·1%) | 2 (0·1%) | | | 16 (1·0%) | 1 (0·1%) | | | | |
| n-around $360^0$ | | | | | | | | | | | | | | |
| an (range= 0-1) | 0·78 (0·41) | 0·59 (0·49) | <0·0001* | <0·001 | 0·83 (0·38) | 0·65 (0·48) | <0·0001* | <0·001 | 0·76 (0·43) | 0·57 (0·50) | <0·0001* | <0·001 | 0·002 | |
| issing, n (%) | 21 (0·7%) | 2 (0·1%) | | | 7 (0·6%) | 1 (0·0%) | | | 13 (0·8%) | 2 (0·1%) | | | | |
| **MMSE score** | | | | | | | | | | | | | | |
| an (range=0-30) | 20·62 (7·93) | 17·41 (9·62) | <0·0001* | <0·001 | 22·95 (7·18) | 19·81 (9·26) | <0·0001* | <0·001 | 19·73 (8·02) | 16·50 (9·59) | <0·0001* | <0·001 | <0·001 | |
| issing, n (%) | 39 (1·3%) | 20 (0·5%) | | | 16 (1·3%) | 4 (0·2%) | | | 23 (1·4%) | 14 (0·6%) | | | | |
| ped results, n (%) | | | <0·0001‡ | <0·001 | | | <0·0001‡ | <0·001 | | | <0·0001‡ | <0·001 | <0·001 | |
| 0-17 | 789 (27·6%) | 1778 (41·2%) | | | 206 (16·7%) | 538 (29·8%) | | | 516 (31·7%) | 1145(45·5%) | | | | |
| 18-22 | 577 (20·2%) | 936 (21·7%) | | | 173 (14·1%) | 366 (20·3%) | | | 367 (22·6%) | 559 (22·2%) | | | | |
| 23-27 | 952 (33·4%) | 1004 (23·2%) | | | 519 (42·2%) | 530 (29·4%) | | | 487 (30·0%) | 526 (20·9%) | | | | |
| 28-30 | 537 (18·8%) | 603 (14·0%) | | | 332 (27·0%) | 371 (20·6%) | | | 255 (15·7%) | 288 (11·4%) | | | | |

Notes: the same as those in Table 1·

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Table 3· Differentials in mortality, cognitive and physical functions between cohorts born in 1893-1898 (aged 100-105 in 1998) and born in 1903-1908 (aged 100-105 in 2008)

| | Two sexes combined | | | | Men | | | | Women | | | | Sex diffe | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Years of birth | | p-value of changes | | Years of birth | | p-value of changes | | Years of birth | | p-value of changes | | p-value (ad | |
| | 1893-1898 (n=2197) | 1903-1908 (n=2809) | Unadjusted | Adjusted¶ | 1893-1898 (n=439) | 1903-1908 (n=600) | Unadjusted | Adjusted¶ | 1893-1898 (n=1758) | 1903-1908 (n=2209) | Unadjusted | Adjusted¶ | 1893-1898 (n=2197) | 1 |
| (standard division) | 101·15 (1·34) | 101·72 (1·55) | <0·0001* | <0·001 | 101·03 (1·34) | 101·52 (1·43) | <0·0001* | <0·001 | 101·18 (1·34) | 101·77 (1·58) | <0·0001* | <0·001 | | |
| **ual death rate** | 40·7% | 38·0% | 0·0521‡ | 0·003 | 45·7% | 41·2% | 0·1479‡ | 0·056 | 39·1% | 37·4% | 0·2735‡ | 0·016 | <0·001 | |
| **lisability score** | | | | | | | | | | | | | | |
| n (range=0-6) | 2·01 (2·09) | 1·58 (2·00) | <0·0001* | <0·001 | 1·57 (1·91) | 1·45 (1·97) | 0·3043* | 0·060 | 2·15 (2·12) | 1·61 (2·00) | <0·0001* | <0·001 | <0·001 | |
| ssing, n (%) | 10 (0·5%) | 0 (0·0%) | | | 1 (0·3%) | 0 (0·0%) | | | 9 (0·5%) | 0 (0·0%) | | | | |
| ed results, n (%) | | | <0·0001‡ | <0·001 | | | 0·0204‡ | 0·002 | | | <0·0001‡ | <0·001 | <0·001 | |
| 0-1 | 1186 (54·2%) | 1820 (64·8%) | | | 274 (62·6%) | 424 (70·7%) | | | 899 (51·4%) | 1399 (63·3%) | | | | |
| 2 | 219 (10·0%) | 229 (8·2%) | | | 43 (9·7%) | 38 (6·4%) | | | 176 (10·1%) | 190 (8·6%) | | | | |
| ≥3 | 784 (35·8%) | 759 (27·0%) | | | 121 (27·6%) | 137 (22·9%) | | | 674 (38·5%) | 620 (28·1%) | | | | |
| **performance score** | | | | | | | | | | | | | | |
| d-up from chair | | | | | | | | | | | | | | |
| n (range= 0-1) | 0·62 (0·37) | 0·57 (0·37) | <0·0001* | 0·001 | 0·70 (0·36) | 0·63 (0·37) | 0·0017* | 0·006 | 0·59 (0·37) | 0·56 (0·37) | 0·0021* | 0·018 | <0·001 | |
| ssing, n (%) | 36 (1·7%) | 12 (0·4%) | | | 8 (1·9%) | 0 (0·0%) | | | 27 (1·6%) | 12 (0·5%) | | | | |
| a book from floor | | | | | | | | | | | | | | |
| n (range= 0-1) | 0·56 (0·39) | 0·49 (0·40) | <0·0001* | <0·001 | 0·66 (0·38) | 0·57 (0·41) | 0·0002* | 0·006 | 0·52 (0·39) | 0·47 (0·39) | <0·0001* | <0·001 | <0·001 | |
| ssing, n (%) | 51 (2·3%) | 7 (0·3%) | | | 12 (2·7%) | 0 (0·0%) | | | 39 (2·2%) | 7 (0·3%) | | | | |
| n-around $360^0$ | | | | | | | | | | | | | | |
| n (range= 0-1) | 0·52 (0·50) | 0·37 (0·48) | <0·0001* | <0·001 | 0·67 (0·47) | 0·45 (0·50) | <0·0001* | <0·001 | 0·47 (0·50) | 0·35 (0·48) | <0·0001* | <0·001 | <0·001 | |
| ssing, n (%) | 12 (0·6%) | 2 (0·1%) | | | 4 (1·0%) | 0 (0·0%) | | | 8 (0·4%) | 1 (0·1%) | | | | |
| **MSE score** | | | | | | | | | | | | | | |
| n (range=0-30) | 14·63 (9·44) | 11·63 (10·12) | <0·0001* | <0·001 | 17·92 (9·19) | 14·95(10·45) | <0·0001* | <0·001 | 13·54 (9·27) | 10·82 (9·87) | <0·0001* | <0·001 | <0·001 | |
| ssing, n (%) | 44 (2·0%) | 55 (2·0%) | | | 9 (2·0%) | 18 (3·1%) | | | 35 (2·0%) | 37 (1·7%) | | | | |
| ed results, n (%) | | | <0·0001‡ | <0·001 | | | 0·0022‡ | <0·001 | | | <0·0001‡ | <0·001 | <0·001 | |
| 0-17 | 1192 (55·3%) | 1837 (66·5%) | | | 172 (40·0%) | 300 (51·2%) | | | 1040 (60·3%) | 1528 (70·2%) | | | | |
| 18-22 | 420 (19·5%) | 378 (13·7%) | | | 89 (20·6%) | 87 (14·9%) | | | 330 (19·1%) | 291 (13·4%) | | | | |
| 23-27 | 386 (17·9%) | 380 (13·8%) | | | 107 (24·8%) | 137 (23·5%) | | | 270 (15·6%) | 248 (11·4%) | | | | |
| 28-30 | 158 (7·3%) | 168 (6·1%) | | | 63 (14·6%) | 60 (10·3%) | | | 85 (4·9%) | 109 (5·0%) | | | | |

Notes: the same as those in Table 1·

Table 4· Annual rates of changes in mortality rates, physical and cognitive functions between the oldest-old cohorts born 10 years apart, who were interviewed with the same age in the CLHLS 1998 survey and the 2008 survey

| | 2 cohorts born 10 years apart and aged 80-89 at interviews conducted in 1998 or 2008 | | | 2 cohorts born 10 years apart and aged 90-99 at interviews conducted in 1998 or 2008 | | | 2 cohorts born 10 years apart and aged 100-105 at interviews conducted in 1998 or 2008 | | |
|---|---|---|---|---|---|---|---|---|---|
| | Two sexes combined | men | women | Two sexes combined | men | women | Two sexes combined | men | women |
| **Evidences may support “benefits-** | | | | | | | | | |
| Follow-up death rate | -0·7%$^{\#}$ | -1·3%$^{\#}$ | -0·3% | -0·3%$^{\#}$ | -0·6% | -0·2% | -0·7%** | -1·0%$^{\#}$ | -0·4%* |
| Mean ADL disability score | -2·4%** | -2·8%* | -2·5%* | -2·3%*** | -2·2%** | -2·3%** | -2·3%*** | -0·8%** | -2·8%*** |
| **Evidences may support “costs-of-** | | | | | | | | | |
| Physical performance capacity score | | | | | | | | | |
| Stand-up from chair | -0·7%*** | -0·6%*** | -0·9%*** | -1·0%*** | -0·8%*** | -0·9%*** | -0·8%*** | -1·0%** | -0·5%* |
| Pick-up book from floor | -0·6%*** | -0·4%*** | -0·6%*** | -1·3%*** | -1·1%*** | -1·4%*** | -1·3%*** | -1·4%** | -1·0%*** |
| Turn-around 360$^{0}$ | -1·1%*** | -0·9%*** | -1·4%*** | -2·7%*** | -2·4%*** | -2·8%*** | -3·3%*** | -3·8%*** | -2·8%*** |
| Cognition capacity (MMSE score) | -0·8%*** | -0·7%*** | -0·9%*** | -1·6%*** | -1·4%*** | -1·7%*** | -2·2%*** | -1·7%*** | -2·2%*** |

Note: # p<0·1; * p<0·05; ** p<0·01; *** p<0·001

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