Reading activities compensate for low education-related cognitive deficits

Yue Wang1,2,3, Shinan Wang4, Wanlin Zhu2,3, Na Liang1,2,3, Chen Zhang1,2,3, Yuankun Pei1,2,3, Qing Wang1,2,3, Shiping Li1,2,3* and Jiong Shi1,2,3*

Abstract

Background: The incidence of cognitive impairment is increasing with an aging population. Developing effective strategies is essential to prevent dementia. Higher education level is associated with better baseline cognitive performance, and reading activities can slow down cognitive decline. However, it is unclear whether education and reading activities are synergistic or independent contributors to cognitive performance.

Methods: This was a sub-study of an ongoing prospective community cohort of China National Clinical Research Center Alzheimer’s Disease and Neurodegenerative Disorder Research (CANDOR). Demographic and clinical information, educational levels, and reading activities were collected. All participants finished neuropsychological testing batteries and brain MRIs. We analyzed cognitive performance and brain structures with education and reading activities.

Results: Four hundred fifty-nine subjectively cognitively normal participants were enrolled in the study. One hundred sixty-nine (36.82%) of them had regular reading activities. Participants in the reading group had better performance in all cognitive tests compared with those in the non-reading group, but no difference in brain MRI variables. Participants with higher education levels (more than 13 years) had better cognitive performance and higher hippocampal volumes. In low education groups (less than 12 years), more reading activities were associated with better cognitive test scores.

Conclusions: Both education and reading activities are important and synergistic for baseline cognitive function. Higher education level is associated with larger hippocampal volumes. Education may stimulate the growth and development of the hippocampus. Reading activities help to maintain and improve cognitive function in people with low levels of education.

Trial registration: NCT04320368.

Keywords: Reading activities, Education, Cognition

Introduction

Aging is the most important risk factor for dementia. With an aging population, dementia has cast an enormous social and economic burden around the world [1, 2]. Developing effective strategies is essential to prevent dementia [3]. It has been reported there are modifiable risk factors for dementia and modifying 12 of them may prevent or delay up to 40% of dementia [4]. The Finnish Geriatric Intervention Study to Prevent Cognitive Impairment and Disability (FINGER), a multicenter randomized controlled trial, reported beneficial effects on cognition through multimodal intervention including cognitive training [5]. Reading activities and other mental stimulation help to slow down cognitive decline [6, 7].

*Correspondence: drlishiping@163.com; jiongshi@ncrcnd.org.cn
1 Department of Neurology, Beijing Tiantan Hospital, Capital Medical University, Beijing, China
Full list of author information is available at the end of the article
High education level is associated with better cognitive performance and lower likelihood to have Alzheimer’s disease (AD) [8, 9]. High education level may delay cognitive decline in individuals with subjective cognitive decline [10, 11]. However, although education is associated with baseline cognitive performance, it doesn't affect the rate of cognitive decline [12], nor does it affect the neuropathological changes related to dementia, such as amyloid plaques and tangles [13].

Previous research compared the influence of reading activities and education on cognition and found that reading activities were associated with a lower risk of dementia even in late life, independent of education and other related factors [6, 7], while another study demonstrated that reading activities have a stronger relationship than education with executive function tests [14].

It is inconclusive whether reading activities and education are synergistic or independent contributors to cognitive performance. In this prospective community-based cohort study, we try to answer the following questions. First, what are the relationships of education and reading activities with cognitive performance on domain-specific tests? Second, are education and/or reading activities associated with brain structure? Third, can reading activities compensate for lower levels of education?

Methods

Study design and participants

This study was a sub-study of an ongoing prospective community-based cohort study of the China National Clinical Research Center Alzheimer’s Disease and Neurodegenerative Disorder Research (CANDOR). CANDOR was started in July 2019 and planned to enroll one thousand and five hundred participants, including individuals with normal cognition (NC), mild cognitive impairment (MCI), and dementia. Demographic information and past medical history were collected. All participants were required to have a study partner to provide an independent evaluation of daily and social functions. They underwent detailed assessments for cognition and functional abilities, a comprehensive neuropsychological battery (described below in “Neuropsychological assessment”) including the Mini-Mental State Examination (MMSE), Clinical Dementia Rating (CDR), and brain MRIs. All enrolled participants for this study (1) were subjectively cognitively normal; (2) aged 40–100 years old; (3) had at least 3 years of education; (4) had no condition known to affect cognitive function, such as Alzheimer’s Disease, vascular dementia, Lewy body dementia, frontotemporal dementia, Parkinson’s disease, epilepsy, stroke, hydrocephalus, multiple sclerosis, traumatic brain injuries, genetic disorders affecting cognition, alcoholism, uncontrolled depression, or other

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**Fig. 1** Study flowchart. Shown is the flowchart of the study enrollment.
**Table 1** Demographic, clinical information, cognitive test scores, and MRI variables in reading and non-reading groups

| Brain structure                                                                 | Reading n=169 | Non-reading n=290 | All patients n=459 | P value  |
|--------------------------------------------------------------------------------|--------------|-------------------|-------------------|---------|
| Average age                                                                     | 60.33±9.04   | 60.03±8.5        | 60.14±8.69        | 0.727   |
| Sex female, (n, %)                                                             | 89, 52.7%    | 171, 59.0%       | 260, 56.6%        | 0.189   |
| Years of education                                                             | 13.88±3.3    | 11.1±3.52        | 12.1±3.69         | <0.001  |
| Hypertension (n, %)                                                            | 57, 33.7%    | 96, 33.1%        | 153, 33.3%        | 0.918   |
| Diabetes (n, %)                                                                | 19, 11.2%    | 34, 11.7%        | 53, 11.5%         | 0.882   |
| Stroke or TIA (n, %)                                                           | 11, 6.5%     | 21, 7.2%         | 32, 7.0%          | 0.851   |
| Coronary heart disease (n, %)                                                   | 14, 8.3%     | 18, 6.2%         | 32, 7.0%          | 0.449   |
| Global CDR score                                                               | 0.11±0.21    | 0.22±0.41        | 0.18±0.36         | 0.001   |
| MMSE                                                                            | 26.15±2.85   | 24.04±4.82       | 24.82±4.32        | <0.001  |
| MoCA                                                                            | 23.38±3.82   | 20.3±5.64        | 21.3±5.29         | <0.001  |
| DST total                                                                      | 12.3±2.34    | 11.0±2.93        | 11.5±2.79         | <0.001  |
| RAVLT total learning                                                           | 39.98±10.06  | 36.26±12.68      | 37.63±11.91       | 0.001   |
| RAVLT long-delayed recall                                                       | 8.01±4.44    | 6.85±3.85        | 7.28±3.74         | 0.001   |
| ROCF copy                                                                       | 32.34±6.91   | 28.48±10         | 30.36±8.83        | 0.001   |
| ROCF long-delayed recall                                                        | 16.5±7.82    | 11.0±9.01        | 13.69±8.87        | <0.001  |
| Stroop D time                                                                  | 16.86±1.13   | 21.8±16.31       | 19.9±13.67        | <0.001  |
| Stroop W time                                                                  | 22.32±8.05   | 26.77±14.46      | 25.1±12.65        | <0.001  |
| TMT-A time                                                                     | 44.18±21.57  | 58.17±35.98      | 52.98±32.11       | <0.001  |
| TMT-B time                                                                     | 101.55±71.89 | 125.32±87.41     | 116.51±82.72      | 0.002   |
| BNT                                                                             | 25.02±3.4    | 21.99±4.37       | 23.11±4.29        | <0.001  |
| SDMT                                                                            | 39.57±13.39  | 32.71±14.89      | 35.25±14.72       | <0.001  |
| CDT                                                                             | 8.79±1.79    | 8.09±2.42        | 8.35±2.23         | <0.001  |
| NPI                                                                             | 1.03±3.17    | 1.83±6.01        | 1.54±5.15         | 0.064   |

Abbreviations: CDR Clinical Dementia Rating, MMSE Mini-Mental State Examination, MoCA Montreal Cognitive Assessment, DST Digit Span Test, RAVLT Rey Auditory Verbal Learning Test, ROCF Rey-Osterrieth Complex Figure Test, TMT Trail Making Test, BNT Boston Naming Test, SDMT Symbol Digit Modalities Test, CDT clock drawing test, NPI Neuropsychiatry Inventory, WM white matter, etIV estimated total intracranial volume
psychiatric disorders; (5) had no uncontrolled neoplasia, or severe pulmonary, cardiovascular, metabolic, infectious, inflammatory, or endocrine diseases. We excluded individuals with less than 3 years of education because people started to learn how to read and write in the third year of elementary school in China. Therefore, people who have less than three years of education will have difficulties in reading.

To assess the relationship between education and leisure reading activities, we defined regular reading activities as reading at least one book per month on average for at least one year. We divided the participants as follows. First, participants were divided into 2 groups based on their reading activities. Reading activities were detailed, including (1) reading materials, such as paper books, e-books, and audio-books; (2) reading content, such as literature books, and non-literature books; (3) the total number of books, which was calculated as the average number of books read per month \( \times 12 \) months \( \times \) years of reading. In participants with reading habits, we divided them further into several groups based on reading years, reading content and reading materials. Second, participants were divided based on their education. Previous studies analyzed education by \( \leq 9 \), 10–12, and \( \geq 13 \) years [15, 16]. In our study, the average education years of all participants were 12.12 years. Therefore, we used a 12-year cut-off to divide participants into two groups: low education (\( \leq 12 \) years, high school education or below, under the average education level) and high education (\( \geq 13 \) years, college education or above, over the average education level). Third, participants were divided into four groups based on education years and reading activities: low education (educational years \( \leq 12 \)) with and without reading activities (groups 1 and 2), and high education (educational years \( \geq 13 \)) with and without reading activities (groups 3 and 4).

**Table 2** The logistic and linear regression analysis of reading in all cognitive tests

| Logistic regression | Model 1, OR, 95% CI | P | Model 2, OR, 95% CI | P |
|---------------------|---------------------|---|---------------------|---|
| Global CDR score (≤0), 330 (71.9%) | 2.012, 1.258–3.218 | 0.004 | 1.416, 0.848–2.365 | 0.210 |
| Linear regression | Model 1, Beta, 95% CI | P | Model 2, Beta, 95% CI | P |
| MMSE | 2.193 [1.463, 2.923] | <0.001 | 1.044 [0.302, 1.787] | 0.006 |
| MOCA | 3.342 [2.486, 4.198] | <0.001 | 1.546 [0.744, 2.348] | <0.001 |
| DST total | 1.240 [0.749, 1.731] | <0.001 | 0.496 [0.003, 0.988] | 0.048 |
| RAVLT learn total | 4.162 [2.208, 6.121] | <0.001 | 1.235 [0.758, 3.227] | 0.224 |
| RAVLT long-delayed recall | 1.185 [0.544, 1.826] | <0.001 | 0.241 [0.426, 0.907] | 0.478 |
| ROCF copy | 3.800 [1.487, 6.114] | 0.001 | 1.296 [0.998, 3.590] | 0.267 |
| ROCF delayed recall | 5.359 [3.138, 7.580] | <0.001 | 3.103 [0.892, 5.314] | 0.006 |
| Stroop D time | –5.162 [–7.712, –2.611] | <0.001 | –3.080 [–5.789, –0.371] | 0.026 |
| Stroop W time | –4.802 [–7.074, –2.530] | <0.001 | –3.304 [–5.694, –0.914] | 0.007 |
| TMT-A time | –14.499 [–19.792, –9.206] | <0.001 | –8.246 [–13.798, –2.694] | 0.004 |
| TMT-B time | –26.290 [–40.525, –12.055] | <0.001 | –7.465 [–22.449–7.519] | 0.328 |
| BNT | 2.961 [2.252, 3.669] | <0.001 | 1.761 [1.048, 2.474] | <0.001 |
| SDMT | 7.385 [5.233, 9.538] | <0.001 | 2.719 [0.693, 4.746] | 0.009 |
| CDT | 0.703 [0.284, 1.121] | 0.001 | 0.219 [0.128, 0.370] | 0.325 |

**Model 1** logistic or linear regression included age and sex

**Model 2** logistic or linear regression included age, sex, and years of education

**Abbreviations:** OR odds ratio for logistic regression, CI confidence interval, CDR Clinical Dementia Rating, MMSE Mini-Mental State Examination, MoCA Montreal Cognitive Assessment, DST Digit Span Test, RAVLT Rey Auditory Verbal Learning Test, ROCF Rey-Osterrieth Complex Figure Test, TMT Trail Making Test, BNT Boston Naming Test, SDMT Symbol Digit Modalities Test, CDT clock drawing test, NPI Neuropsychiatry Inventory
|                                | Education ≤12 years | Education ≥13 years | P    |
|--------------------------------|---------------------|---------------------|------|
| Average age                    | 61.66±8.28          | 57.43±8.78          | <0.001|
| Sex female (n, %)              | 177, 60.2%          | 83, 50.3%           | 0.040|
| Years of education             | 9.79±2.34           | 16.29±0.95          | <0.001|
| Global CDR score               | 0.10±0.24           | 0.22±0.40           | <0.001|
| MMSE                           | 23.74±4.65          | 26.73±2.79          | <0.001|
| MoCA                           | 19.47±5.18          | 24.62±3.61          | <0.001|
| DST total                      | 10.72±2.51          | 12.98±2.68          | <0.001|
| RAVLT total learning           | 8.93±3.32           | 11.07±2.79          | <0.001|
| RAVLT long-delayed recall      | 6.04±3.7            | 8.65±3.53           | <0.001|
| ROCF copy                      | 33.18±6.55          | 28.8±9.53           | <0.001|
| ROCF long-delayed recall       | 17.23±7.96          | 11.74±8.76          | <0.001|
| Stroop D time                  | 22.07±16.02         | 16.25±6.55          | <0.001|
| Stroop W time                  | 27.72±13.85         | 20.54±8.46          | <0.001|
| TMT-A time                     | 59.73±32.17         | 41.09±28.42         | <0.001|
| TMT-B time                     | 136.48±91.03        | 81.31±48.78         | <0.001|
| BNT                            | 21.78±4.47          | 25.44±2.69          | <0.001|
| SDMT                           | 30.22±13.05         | 44.06±13.28         | <0.001|
| CDT                            | 8.00±2.39           | 8.96±1.76           | <0.001|
| NPI                            | 1.75±5.86           | 1.16±3.55           | 0.242|
| Brain structure                 |                     |                     |      |
| Left hippocampal volume, mm²   | 3386.57±435.93      | 3584.61±428.01      | <0.001|
| Left amygdala volume, mm²      | 1634.78±220.55      | 1709.65±215.06      | 0.145|
| Left thalamus volume, mm²      | 6883.74±897.91      | 6867.95±973.97      | 0.864|
| Left caudate volume, mm²       | 3313.07±580.16      | 3289.96±567.13      | 0.697|
| Left putamen volume, mm²       | 4629.44±710.25      | 4605.42±676.78      | 0.73 |
| Left pallidum volume, mm²      | 1931.57±251.23      | 1914.63±250.43      | 0.498|
| Left cortex volume, mm²        | 216.13±923.25       | 212.92±241.25       | 0.188|
| Left cerebral white matter volume, mm² | 223.57±29,777.23   | 218.95±21,041.08    | 0.125|
| Left mean cortical thickness, mm | 2.37±0.12           | 2.38±0.10           | 0.678|
| Right hippocampal volume, mm²  | 3512.3±476.23       | 3710.8±433.37       | <0.001|
| Right amygdala volume, mm²     | 4691.13±49,986.08   | 1777.0±252.54       | 0.563|
| Right thalamus volume, mm²     | 6696.93±380.19      | 6594.12±885.91      | 0.225|
| Right caudate volume, mm²      | 3373.49±565.75      | 3340.36±568.73      | 0.474|
| Right putamen volume, mm²      | 4743.54±678.03      | 4714.12±697.27      | 0.666|
| Right pallidum volume, mm²     | 1928.99±259.36      | 1922.71±272.97      | 0.812|
| Right cortex volume, mm²       | 216.04±23,917.16    | 212.02±26,239.96    | 0.104|
| Right cerebral white matter volume, mm² | 222.78±30,237.45   | 217.819.36±30,845.32| 0.096|
| Right mean cortical thickness, mm | 2.37±0.12           | 2.37±0.11           | 0.800|
| Cortex volume, mm²             | 432.18±47.269.6     | 424.99±51,768.69    | 0.138|
| Subcortex gray volume, mm²     | 54.526.69±603.69    | 54.063.54±617.62    | 0.445|
| Total gray volume, mm²         | 585.324.16±59,164.42| 576.922.21±63,115.96| 0.164|
| Cerebral white matter volume, mm² | 446.359.92±58,982.67| 436.772.07±61,698.97| 0.109|
| WM hyperintensities volume, mm² | 3219.53±4544.25    | 3355.6±51.23.64    | 0.510|
| Brain segmentation volume, mm² | 1,089.19±112,197.33| 1,067.99±118,965.54| 0.110|
| eTIV, mm²                      | 1,443,152.53±151,357.93| 1,422,097.74±162,271.98| 0.199|
| Brain segmentation volume to eTIV, % | 75.67±5.19      | 75.37±5.11          | 0.590|

Abbreviations: CDR Clinical Dementia Rating, MMSE Mini-Mental State Examination, MoCA Montreal Cognitive Assessment, DST Digit Span Test, RAVLT Rey Auditory Verbal Learning Test, ROCF Rey-Osterrieth Complex Figure Test, TMT Trail Making Test, BNT Boston Naming Test, SDMT Symbol Digit Modalities Test, CDT clock drawing test, NPI Neuropsychiatry Inventory, WM white matter, eTIV estimated total intracranial volume
Test B (TMT -B) [20], clock drawing test (CDT), Boston Naming Test (BNT), Digit Span Test (DST), and Symbol Digit Modalities Test (SDMT); and (3) Neuropsychiatry Inventory (NPI). These tests were administered by experienced neuropsychologists who were blinded to group assignment.

MRI assessment
All participants completed the brain MRI to exclude other demonstrable neurological diseases. Quantitative measures of signal-to-noise ratio, uniformity, and geometric distortion were conducted in each research center. 3.0 T-MRI was used with the scanning thickness not exceeding 1.5mm. The three-dimensional T1 weighted images were corrected for intensity non-uniformity with the N4 algorithm. Brain surface was reconstructed using FreeSurfer (version 7.2.0, http://surfer.nmr.mgh.harvard.edu/) recon-all pipeline. The cortical thickness and volume of the total brain, nuclei, gray matter white matter, and white matter lesion were all obtained with this pipeline. Regional cortical thickness was obtained and statistical analysis was performed.

Statistical analysis
The analysis was conducted with SPSS 24.0. Continuous variables were characterized as mean plus and/or minus standard deviations (SD). T-test or nonparametric test was used by the characteristic of the distribution. Categorical variables were analyzed by Pearson’s χ² tests. We performed logistic regression analysis to evaluate the association between reading and CDR (CDR=0 or >0), linear regression analysis for the association of reading and neuropsychological assessment, and linear regression analysis for education and brain structure. The regression analyses were independent of age and sex in Table 2 model 1 and Table 5. The regression analyses were independent of age, sex, and education in Table 2 model 2. We also performed the collinearity analysis in every linear regression analysis, and all the results showed no collinearity between every included independent variable.

Results
From July 31, 2019, to August 1, 2021, 694 individuals were screened from communities in Beijing, Shijiazhuang, and Langfang, all in northern China. They completed standard baseline assessments. 459 were enrolled in the study who had both valid brain MRI examination and cognitive evaluation (Fig. 1). Among them, 169 (36.82%) had regular reading activities. There was no significant difference in age, sex, medical history, and mood assessment (NPI) between the two groups (Table 1). The reading group had more years of education and better cognitive performance than the non-reading group, including CDR, MMSE, MoCA, DST, RAVLT, ROCF, Stroop D and W time, TMT-A and B, BNT, SDMT, and CDT. However, there was no difference in cortical thickness and hippocampal volume in either hemisphere between the two groups.

Logistic and linear regression were used to assess confounding factors (Table 2). Reading activities were associated with better cognitive performance, such as MMSE (beta 2.193, 95%CI: 1.463–2.923, P<0.001), independent of age and sex in model 1. In model 2, when education was taken into account, reading activities showed similar effects in MoCA and Boston Naming; significant but less effects in MMSE, DST, ROCF delayed recall, Stroop D and W time, TMT-A and SDMT, but no effects in CDR, RAVLT, ROCF copy, TMT-B, and CDT.

![Fig. 2](image-url) Hippocampal volumes at different education levels. Shown is the right (open box) and left (closed dot) hippocampal volume associated with different education levels.
Table 4  Cognitive performance and brain structure comparison by education level and reading activities

|                      | Group 1 | Group 2 | Group 3 | Group 4 |
|----------------------|---------|---------|---------|---------|
| n                    | 71      | 223     | 98      | 67      |
| Age                  | 62.66±9.79 | 61.34±7.73 | 58.63±8.09 | 55.67±9.5 | 0.825 |
| Gender female (n, %) | 39, 54% | 138, 61% | 50, 51% | 33, 43% | 0.824 |
| Education years      | 10.44±1.95 | 9.58±2.42 | 16.37±1.08 | 16.18±0.72 | 0.180 |
| Global CDR score     | 0.14±0.23 | 0.24±0.44 | 0.08±0.20 | 0.13±0.28 | 0.236 |
| MMSE                 | 25.04±3.13 | 23.33±4.97 | 26.94±2.35 | 26.42±3.34 | 0.241 |
| MoCA                 | 21.26±4.05 | 18.9±5.37 | 24.9±2.82 | 24.22±4.52 | 0.280 |
| DST total            | 11.59±2.27 | 10.45±2.53 | 12.82±2.26 | 13.21±3.19 | 0.387 |
| RAVLT total learning | 35.97±9.55 | 33.81±11.85 | 42.85±9.45 | 44.44±12.02 | 0.345 |
| RAVLT long-delayed recall | 6.07±3.43 | 6.03±3.79 | 8.73±3.29 | 8.53±3.88 | 0.726 |
| ROCF copy            | 30.36±8.25 | 27.99±10.07 | 33.96±5.08 | 30.84±9.53 | 0.186 |
| ROCF long-delayed recall | 14.33±8.32 | 10.39±8.73 | 18.31±6.95 | 14.05±9.92 | 0.096 |
| Stroop D time        | 18.19±7.84 | 23.31±17.69 | 15.91±4.35 | 16.75±8.88 | 0.419 |
| Stroop W time        | 24.97±9.69 | 28.59±14.85 | 20.42±6 | 20.72±11.21 | 0.844 |
| TMT-A time           | 50.89±25.93 | 62.56±33.49 | 39.39±16.34 | 43.62±40.19 | 0.419 |
| TMT-B time           | 128.57±91.74 | 139.01±90.87 | 82.26±44.79 | 79.91±54.49 | 0.764 |
| BNT                  | 23.97±3.87 | 21.08±4.43 | <0.001 | 25.77±2.81 | 0.057 |
| SDMT                 | 33.07±12.71 | 29.31±13.05 | 44.21±11.89 | 43.84±15.18 | 0.864 |
| CDT                  | 8.59±1.92 | 7.82±2.50 | 8.94±1.69 | 8.98±1.87 | 0.870 |
| NPI                  | 1.31±4.25 | 1.89±6.29 | 0.478 | 0.83±2.09 | 1.65±4.97 | 0.206 |
| Brain structure      |         |         |         |         |
| Left hippocampal volume, mm³ | 3391.25±1422.13 | 3372.73±4198.86 | 3580.93±4551.11 | 3587.09±4112.0 | 0.93 |
| Left amygdala volume, mm³ | 1487.93±400.96 | 1494.7±333.99 | 1444.95±319.72 | 1443.14±289.65 | 0.971 |
| Left thalamus volume, mm³ | 6927.86±912.39 | 6868.82±894.71 | 6844.53±902.39 | 6902.71±1077.97 | 0.713 |
| Left caudate volume, mm³ | 3274.19±590.97 | 3326.22±577.32 | 3347.72±546.78 | 3204.22±589.96 | 0.118 |
| Left putamen volume, mm³ | 4613.36±742.16 | 4634.88±700.9 | 4647.23±600.29 | 4543.36±777.51 | 0.344 |
| Left pallidum volume, mm³ | 1958.16±291.24 | 1922.58±236.29 | 1926.63±253.55 | 1896.81±246.62 | 0.463 |
| Left cortex volume, mm³ | 215,000.93±24,471.4 | 216,524.19±23,482.27 | 212,619.25±24,800.12 | 213,736.89±27,526.83 | 0.857 |
| Left cerebral white matter volume, mm³ | 225,861.59±35,115.03 | 222,804.26±27,795.56 | 217,545.76±29,530.28 | 221,041.16±33,286.15 | 0.488 |
| Left mean cortical thickness, mm | 2.37±0.12 | 2.36±0.11 | 2.38±0.11 | 2.38±0.1 | 0.796 |
| Right hippocampal volume, mm³ | 3533.42±467.04 | 3449.84±500.66 | 3695.9±417.79 | 3720.84±445.47 | 0.723 |
| Right amygdala volume, mm³ | 1638.97±387.11 | 1671.78±333.05 | 1646.86±334.66 | 1639.52±320.52 | 0.89 |
| Right thalamus volume, mm³ | 6739.93±910.74 | 6682.39±802.96 | 6571.9±886.17 | 6627.11±891.5 | 0.701 |
| Right caudate volume, mm³ | 3326.03±602.96 | 3389.53±553.2 | 3396.05±628.68 | 3257.71±572.69 | 0.161 |
| Right putamen volume, mm³ | 4702.98±639.94 | 4757.25±691.4 | 4723.38±655.7 | 4700.38±759.94 | 0.839 |
| Right pallidum volume, mm³ | 1939.62±285.7 | 1925.39±250.47 | 1935.71±280.49 | 1903.42±262.42 | 0.466 |
| Right cortex volume, mm³ | 214,709.43±24,120.85 | 216,498.29±23,889.7 | 211,079.33±26,149.49 | 213,429.13±26,517.63 | 0.581 |
Table 4 (continued)

|                          | Group 1 n=71 | Group 2 n=223 | P   | Group 3 n=98 | Group 4 n=67 | P   |
|--------------------------|--------------|---------------|-----|--------------|--------------|-----|
| Right cerebral white matter volume, mm² | 225,512.97±34,160.89 | 221,859.89±27,599.24 | 0.42 | 215,805.29±29,593.22 | 220,808.98±32,622.88 | 0.317 |
| Right mean cortical thickness, mm | 2.37±0.12 | 2.35±0.11 | 0.142 | 2.38±0.11 | 2.37±0.11 | 0.427 |
| Cortex volume, mm² | 429,710.36±48,310.18 | 433,022.48±47,001.73 | 0.613 | 423,698.58±50,582.34 | 426,806.01±53,831.66 | 0.712 |
| Subcortex gray volume, mm² | 54,504.63±6480.09 | 54,534.15±5891.59 | 0.972 | 54,151.2±5827.67 | 53,933.42±6713.47 | 0.828 |
| Total gray volume, mm² | 582,730.42±62,282.68 | 586,201.27±58,202.35 | 0.672 | 576,181.75±62,013.7 | 578,021.34±65,196.6 | 0.858 |
| Cerebral white matter volume, mm² | 451,374.56±69,166.21 | 444,664.14±55,202.29 | 0.463 | 433,351.05±58,867.31 | 441,850.14±65,823.54 | 0.396 |
| WM hyperintensities volume, mm² | 3602.52±4963.72 | 3090.02±4398.62 | 0.416 | 3925.16±6044.47 | 2460.48±3165.75 | 0.048 |
| Brain segmentation volume, mm² | 1,093,169.74±123,689.54 | 1,087,857.27±108,324.4 | 0.733 | 1,065,497.73±113,587.95 | 1,071,699.19±127,357.94 | 0.748 |
| eTIV, mm² | 1,440,816.13±159,459 | 1,443,942.62±148,911.25 | 0.882 | 1,422,070.61±165,054.25 | 1,422,138.01±159,346.57 | 0.998 |
| Brain segmentation volume to eTIV, % | 76.03±5.26 | 75.55±5.18 | 0.507 | 75.26±6.19 | 75.54±6.03 | 0.783 |

Four groups: low education (educational years ≤12) with and without reading activities (groups 1 and 2) and high education (educational years ≥13) with and without reading activities (groups 3 and 4).

Abbreviations: CDR Clinical Dementia Rating, MMSE Mini-Mental State Examination, MoCA Montreal Cognitive Assessment, DST Digit Span Test, RAVLT Rey Auditory Verbal Learning Test, ROCF Rey-Osterrieth Complex Figure Test, TMT Trail Making Test, BNT Boston Naming Test, SDMT Symbol Digit Modalities Test, CDT clock drawing test, NPI Neuropsychiatry Inventory, WM white matter, eTIV estimated total intracranial volume

Education had a remarkable effect on cognitive performance (Table 3). Participants with high education scored higher in all cognitive tests than those with low education. They also have higher hippocampal volumes on both sides (Fig. 2).

Reading years and reading content had little impact on cognitive performance and brain structure (Supplemental Tables 1 and 2). Reading e-books showed no obvious cognitive benefits than paper books, and listening to audio-books performed better in MoCA, BNT, and SDMT (Supplemental Table 3).

To assess if reading activities have a compensatory effect for low education, we divided participants into four groups: low education (educational years ≤12) with and without reading activities (groups 1 and 2), and high education (educational years ≥13) with and without reading activities (groups 3 and 4). Reading activities improved most cognitive tests (except RAVLT, ROCF copy, and TMT-B) in the low education group (group 1 better than group 2, Table 4). By reading more books, participants with low education could achieve similar or even better cognitive scores than those with high education in MMSE, MoCA, DST, and BNT (Fig. 3). In the high education groups, reading activities showed few effects probably due to ceiling effects (group 3 similar to group 4, Table 4).

The linear regression related to hippocampal volume on either side showed that years of education influenced hippocampal volume with beta 14.999 [4.906, 25.092], P=0.004 and beta 2 15.816 [4.949, 26.683], P=0.004 (Table 5), regardless of age and sex.

Discussion
In this community-based subjectively cognitively normal population, participants with regular reading activities showed better cognitive performance in overall cognitive abilities, attention, memory, language, visuospatial and executive function. This effect is independent of brain volume, especially hippocampal volume. A prospective cohort study showed that increased participation in cognitive activities (including reading) was associated with better memory [21]. Although reading activities involve multiple brain areas, subgroup analysis of the FINGER study has shown that the multi-domain intervention has no effects on brain volume, cortical thickness, and white matter lesion [22].

Education was related to cognition across all tested domains. Reading is associated with all tested domains controlled with age and sex. However, when education was included in the analysis, the effect of reading on cognitive assessment weakened, indicating a stronger correlation between education level and cognition. Reading is a complex task that involves various brain areas, including the insular and frontal opercular cortex, lateral temporal cortex, and early auditory cortex with the positive reaction and inferior temporal and...
motor cortex with the negative reaction [23]. However, we did not see a difference in the cortical thickness and the hippocampus between reading and non-reading groups. This suggests that reading activities may help to improve cognitive function in participants with low education level (≤12 years) independent of brain

Table 5 The linear regression of education and hippocampal volume

|                          | Model 1, beta, 95% CI                  | P     | Model 2, beta, 95% CI                  | P     |
|--------------------------|---------------------------------------|-------|---------------------------------------|-------|
| Years of education       | 14.999, [4.906, 25.092]               | 0.004 | 15.816, [4.949, 26.683]               | 0.004 |
| Education ≥13            | 23.020, [3.868, 42.172]               | 0.019 | 22.114, [1.476, 42.753]               | 0.036 |

Model 1, data of left hippocampal volume were analyzed as results, age, and sex were in linear regression
Model 2, data of right hippocampal volume were analyzed as results, age, and sex were in linear regression
Abbreviations: CI confidence interval
volume. In some cognitive domains, the cognitive performance gap caused by education level is decreased with the increase in reading activities. Reading is a good way to fill the cognitive gap brought about by lack of education, especially in language, non-verbal memory, and executive function.

In this study, participants with high education level had higher hippocampal volume. Larger hippocampal volumes may be associated with higher intelligence quotient (IQ), practice in hippocampus-related function (e.g., learning and memory), lifestyle, and medial/historical factors (neurotoxic effects of obesity, diabetes mellitus, hypertension, hypoxic brain injury, obstructive sleep apnea, bipolar disorder, clinical depression, and head trauma) [24]. Higher education level is favorable to the neurological task performance [10, 12, 25–27], but not to AD-related pathology [28].

MMSE and MoCA are screening tests for cognition. Their cut-off scores are based on education levels. In this study, participants with low education but reading more books showed no difference in MMSE and MoCA compared with participants with high education level. It suggests that people with low education but who read a lot probably should be screened at the same level as those who are more educated.

Audio devices are a new form of reading activities and have become popular. It is suggested that audiobooks are probably better than non-audio books at improving cognitive function. Young children learned more words from the e-book and from the audio narrator than print books [29]. Different types of books may influence the ability to retrieve information. Listening to audiobooks may stimulate more brain areas to have positive effects on cognition, especially memory and executive function. Since poor vision is not uncommon in the elderly, audiobooks are a better tool for old people to enjoy reading activities.

The strength of this study is a large community-based cohort with detailed neuropsychological testing batteries and brain MRI analysis. But the study has several limitations. First, this is an observational, cross-sectional study. Correlation does not imply causation. To study the causative effect of reading activities on cognitive function, a randomized clinical trial is warranted. Participants with certain education levels would be assigned with different reading activities. Other intellectual activities besides leisure reading would also be taken into account. Second, we enrolled participants with subjectively normal cognitive function to represent community-based cohorts. The average CDR was 0.18 although a few participants with a CDR more than 0.5. Ongoing longitudinal follow-ups will allow us to assess the relationship between risk/protective factors and the conversion to dementia. Third, all participants were enrolled from northern China. There is likely a difference in culture, education, and environmental factors among different regions in China. To expand population sampling is needed in future studies. Fourth, higher education level is associated with larger hippocampal volumes. One explanation is that education may stimulate the growth and development of the hippocampus. Alternatively, people with larger hippocampal volume may have a better chance to acquire higher education. Fifth, the study may have a recall bias since reading activities were recorded by self-reported questionnaires. People might under- or overestimate the books they read. Objective measures (e.g., a shopping receipt of purchased books) may help to validate the finding. Finally, reading activities as measured by reading books are mainly leisure reading. It does not take into account of all activities related to intellectual activities. Individuals who do a lot of reading or research at work but have little time in reading books outside of work may be underestimated in reading activities.

Conclusions
Participants in reading groups with less education (educational years <12) had better cognitive performance than the ones in non-reading groups. Education affects more than reading habits in every cognitive domain and in hippocampal volume.

Abbreviations
CANDOR: China National Clinical Research Center Alzheimer’s Disease and Neurodegenerative Disorder Research; FINGER: Finnish Geriatric Intervention Study to Prevent Cognitive Impairment and Disability; AD: Alzheimer’s disease; MRI: Magnetic resonance imaging; NC: Normal cognition; MCI: Mild cognitive impairment; MMSE: Mini-Mental State Examination; CDR: Clinical Dementia Rating; MoCA: Montreal Cognitive Assessment; RAVLT: Rey Auditory Verbal Learning Test; ROCFT: Rey-Osterrieth Complex Figure Test; TMT: Trail Making Test; CDT: Clock drawing test; BNT: Boston Naming Test; DST: Digit Span Test; SDMT: Symbol Digit Modalities Test; NPI: Neuropsychiatry Inventory; SD: Standard deviations; OR: Odds ratio; CI: Confidence interval; WM: White matter; eTIV: Estimated total intracranial volume.

Supplementary Information
The online version contains supplementary material available at https://doi.org/10.1186/s13195-022-01098-1.

Additional file 1: Supplemental Table 1. Cognitive performance of participants having different reading years.

Additional file 2: Supplemental Table 2. Cognitive performance of participants reading different content.

Additional file 3: Supplemental Table 3. Cognitive performance of participants using different reading materials.
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Authors’ contributions

SL and JS designed the study; YW, SL, and JS did the scientific literature search. YW, SW, SL, NL, CZ, YP, and QW collected data; YW, WZ, SL, and JS analyzed data. YW and SL created the tables. YW, SL, and JS wrote and all authors edited the report. All authors read and approve the manuscript.

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Availability of data and materials

SL and JS had full access to all of the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis.

Declarations

Ethics approval and consent to participate

This protocol was approved by the Institutional Review Board of Beijing Tiantan Hospital (approval number: KY-2019-004-007) and was in accordance with relevant guidelines and regulations. Written informed consent was obtained from each participant.

Consent for publication

Not involving any person’s data in any form.

Competing interests

The authors declare that they have no competing interests.

Author details

1 Department of Neurology, Beijing Tiantan Hospital, Capital Medical University, Beijing, China. 2 National Clinical Research Center for Neurological Diseases, Beijing Tiantan Hospital, Capital Medical University, Beijing, China. 3 Advanced Innovation Center for Human Brain Protection, Capital Medical University, Beijing, China. 4 Department of Neurology, Hebei Yanda Hospital, Sanhe, Hebei Province, China.

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