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Low cortical iron and high entorhinal cortex volume promote cognitive functioning in the oldest-old

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Abstract

The aging brain is characterized by an increased presence of neurodegenerative and vascular pathology. However, there is substantial variation regarding the relationship between an individual's pathological burden and resulting cognitive impairment. To identify correlates of preserved cognitive functioning at highest age, the relationship between β-amyloid plaque-load, presence of small vessel cerebrovascular disease (SVCD), iron-burden and brain atrophy was investigated. 80 cognitively unimpaired participants (44 oldest-old, aged 85–96; 36 younger-old, aged 55–80) were scanned by integrated PET-MRI for assessing β-regional amyloid plaque-load (18F-Flutemetamol), white matter hyperintensities as an indicator of SVCD (FLAIR-MRI) and iron-load (Quantitative Susceptibility Mapping). For the oldest-old group, lower cortical volume, increased β-amyloid plaque-load, prevalence of SVCD and lower cognitive-performance in the normal range was found. However, compared to normal-old, cortical iron burden was lower in the oldest old. Moreover, only in the oldest-old, entorhinal cortex volume positively correlated with β-amyloid plaque-load. Our data thus indicate that the co-occurrence of aging-associated neuropathologies with reduced QSM-measures of cortical iron-load constitutes a lower vulnerability to cognitive loss.

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Competing Financial Interests statement

Dr. Peter van Zijl is a paid lecturer for Philips Healthcare and is the inventor of technology that is licensed to Philips. This arrangement has been approved by The Johns Hopkins University in accordance with its Conflict of Interest policies.

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Keywords

PET; MRI; beta-Amyloid; iron; QSM; oldest-old; cognitive reserve; maintenance; APOE

Introduction

While advanced age is associated with substantial brain change and increased risk for cognitive decline, several studies on populations of older adults have revealed high levels of cognitive functioning despite considerable brain pathology. The resilience against such pathologies can be described as the brain's reserve; the cognitive and physiological properties that allow an individual to better tolerate age-related brain alterations and neuropathological burden before cognitive performance is impaired (Barulli and Stern, 2013). Alternatively, maintained cognitive functioning could be attributed not to reserve, but to the presence of neuroprotective factors such as genetic variants, or alterations in clearance mechanisms that prevent the accumulation of neuropathologies at high age (Nyberg et al., 2012). Individuals in the age-group of 85 years and above ("oldest-old") are of particular interest when investigating both the relationship between manifest brain change and risk for Alzheimer's disease (AD) (Kawas et al., 2013), and potential physiological factors that promote resistance against age-related neuropathological burden (Nyberg et al., 2012; Rogalski et al., 2013). While Apolipoprotein E ε4 (APOE4) carrier-status is the strongest known risk factor for sporadic AD in the younger-old (Corder et al., 1993) and has been linked to increased β-amyloid plaque burden in the cognitively normal (Hollands et al., 2017), there also are reports suggesting no association of APOE4 status with incident dementia or compensatory reserve mechanisms in the oldest-old (Corrada et al., 2013; Garibotto et al., 2012).

Several studies have reported substantial discrepancies between measurable neuropathology and expected cognitive performance. This includes increased levels of β-amyloid plaques, which may reflect risk for future cognitive decline due to AD (Kawas et al., 2013; Sperling et al., 2009) and can be measured in cognitively healthy older adults (Mintun et al., 2006). In addition, regional atrophy was linked to AD-associated neurodegenerative brain change, typically affecting hippocampus and entorhinal cortex years before manifestation of cognitive decline (de Leon et al., 1989; Frisoni et al., 2010). The coexistence of β-amyloid plaques with other non-AD specific neurodegenerative alterations could indicate the greatest risk for progression to cognitive decline (Jagust, 2016; Mormino et al., 2014). For example, small-vessel cerebrovascular disease (SVCD) is a frequent finding in cognitively healthy older adults, and relates to pathogenic markers of AD including β-amyloid plaque burden and regional atrophy, thus increasing risk for cognitive dysfunction (Guzman et al., 2013). Cerebral accumulation of iron is another neuropathological finding associated with aging, but also with neurodegenerative disorders including AD (Ayton et al., 2015; Ayton et al., 2017). Local iron accumulations in the vicinity of β-amyloid plaques may reflect both oxidative stress (Andersen et al., 2014; Meadowcroft et al., 2009; Rottkamp et al., 2001) and presence of activated microglia (Zeineh et al., 2015). Additionally, activated proinflammatory microglia have been correlated to β-amyloid associated neurodegeneration and cognitive impairment (Fan et al., 2017; Serrano-Pozo et al., 2016), suggesting that in

vivo measures of iron could indicate both oxidative stress and β-amyloid associated neurodegeneration (Ayton et al., 2017; Derry and Kent, 2017; van Bergen et al., 2016b).

State-of the art neuroimaging using multiple imaging modalities can provide in vivo information on various neuropathological burdens. Radioactive tracers may be used for measuring cerebral β-amyloid plaque burden by Positron-Emission-Tomography (PET) (Klunk et al., 2004; Vandenberghe et al., 2010). T1 weighted MRI is an established measure for regional atrophy in AD (Frisoni et al., 2010) and SVCD severity can be inferred from white matter hyperintensities (WMH), as measured by Fluid-Attenuated Inversion Recovery (FLAIR) MRI (Guzman et al., 2013). Recent developments on quantitative susceptibility mapping (QSM) techniques (Deistung et al., 2013; Li et al., 2011; Lim et al., 2013; Schweser et al., 2012) allow for in vivo measures of cerebral iron-load.

While research on oldest-old populations may significantly advance knowledge on both protective and risk factors in AD and other age-related cognitive disorders (Kawas et al., 2013), not much is known on mechanisms that determine the relationship between presence of major neuropathologies and preserved cognitive functioning in the oldest-old. Aims of the current study therefore were 1.) to assess prevalence of aging-related brain change in a population of cognitively healthy older adults by assessing cerebral β-amyloid burden, differences in structural volume as an indicator of present neurodegenerative change, cerebral iron-load and the regional distribution of WMH as a proxy of SVCD; 2.) to characterize brain-physiology and neural mechanisms associated with preserved cognitive function, by assessing interactive relationships of pathological alterations and differences between cognitively healthy oldest-old and younger-old.

Methods

Participants

For the current study, two cohorts at the Hospital for Psychogeriatric Medicine and Institute for Regenerative Medicine (IREM), University of Zurich (UZH), Switzerland were combined resulting in a total sample of 80 healthy and cognitively unimpaired older adults. Within the recruited sample, two groups were compared: 36 "younger-old" (ages 55–80 years) and 44 "oldest-old" (ages 85–96 years) participants. Study procedures were in concordance with Human Research Act of Switzerland as well as with the declaration of Helsinki. Written informed consent was obtained from all participants before inclusion in the study.

Inclusion criteria were: preserved everyday functioning and no significant cognitive impairment, as assessed by the CERAD neuropsychological battery (Sotaniemi et al., 2012) and additional tests used in earlier studies of ours (van Bergen et al., 2016b), including Mini Mental State Examination (MMSE), Verbal Learning and Memory Test (VLMT), Boston Naming Test (BNT), Trail Making Test B/A, and Stroop inference test. Exclusion criteria included: significant medication or drug abuse with possible effects on cognition, inability to partake MRI, MRI scans with the evidence of infection or infarction, clinically relevant changes in red blood cell count, serious medical or neuropsychiatric illness and significant exposure to radiation.

MRI data acquisition

All participants were scanned using a 3T GE SIGNA PET-MR whole-body scanner (GE Medical Systems, Milwaukee, WI, USA) equipped with an 8-channel head coil. T1-weighted BRAVO images (TI=450ms, voxel size=1×1×1mm3, flip-angle=12°, ASSET factor=2, scan time=6:00min) were acquired for anatomical referencing and automated image segmentation. MR phase measurements used for QSM calculation were acquired using a multi-echo 3D gradient recalled echo (GRE) sequence with 6 echoes (TR/TE1/ΔTE=40/6/4ms, voxel size=1×1×1mm3, flip angle=15°, bandwidth=±62.5 kHz, flow compensated, ASSET factor=2, scan time=7:53min). Phase data acquired with an echo time in the range of 18–26ms was used for QSM reconstruction. Images used to determine WMH were acquired using a CUBE FLAIR sequence (TR=6500ms, TE=134, ARC factor=2, voxel size=1×1×1.2mm^3, bandwidth=±31.25 kHz, scan time=6:07min).

Assessment of structure volumes

To assess regional differences, the T1-weighted image was segmented using a multi-atlas matching approach consisting of 143 bilateral Regions of Interest (ROIs) developed as part of the Johns Hopkins University brain atlas. The atlas system is optimized for the parcellation of potential non-healthy brains by applying a Multiple-Atlas Likelihood Fusion algorithm and Ontology Level Control technology on the JHU multi-atlas sets (Djamanakova et al., 2014; Mori et al., 2016; Tang et al., 2013). Specifically, the atlas set of 26 participants aged between 50 and 90 years was used.

To normalize different brain sizes across participants, individual structural volume was corrected with the following approach: *Corrected structure volume = Original structure volume × (whole sample mean intracranial volume / participant intracranial volume)* (van Bergen et al., 2016b). Twelve gray-matter ROIs were selected based on earlier reports on distribution of brain pathology at early stages of AD (Frisoni et al., 2010; Serrano-Pozo et al., 2011).

ROI-masks were eroded with two pixels to account for partial volume effects before being used as a mask to analyze average iron-load (QSM), β-amyloid burden and WMH detection. These imaging volumes were first re-sliced to the individual's T1 space, in which the atlas was defined, before further analysis.

Quantitative susceptibility mapping (QSM) for measuring brain iron-load

Multiple processing steps were performed to calculate from the acquired MR phase images the quantitative susceptibility maps of which local cerebral iron-load was assessed. First, phase unwrapping was performed using Laplacian based phase unwrapping (Li et al., 2011). A brain mask was then obtained by skull-stripping the GRE magnitude image acquired at TE of 14ms using FSL's brain extraction tool (BET, FMRIB Oxford, UK). The unwrapped phase images were then divided by 2π*TE to obtain an image of the frequency shift in Hz for each echo. Subsequently, background fields were eliminated with the sophisticated harmonic artifact reduction for phase data (SHARP) (Schweser et al., 2011) approach using a variable spherical kernel size with a maximum radius of 4mm and a regularization parameter of 0.05 (Schweser et al., 2011; Wu et al., 2012b). After removal of background

fields, the resulting images of the three echoes were averaged to obtain a higher SNR as compared to single echo reconstruction (Wu et al., 2012a). Inverse dipole calculations to obtain the susceptibility maps were performed using an iLSQR based minimization (Li et al., 2015). The means of the standard deviations of susceptibility in commonly accepted QSM reference regions, such as various white matter bundles and sections of the cerebrospinal fluid, were evaluated to select the region with the lowest mean standard deviations as the reference region (Deistung et al., 2013). For clarity and consistency with earlier studies, changes in susceptibility values will be referred to as changes in iron-load, due to the previously demonstrated correlation of susceptibility values with tissue iron-load in brain gray matter (Deistung et al., 2013; Li et al., 2011; Lim et al., 2013; Schweser et al., 2012).

Flutemetamol-PET for estimation of brain β-amyloid plaque burden

Flutemetamol-PET was used to estimate individual local brain β-amyloid plaque burden (Vandenberghe et al., 2010). Individual dose of 140MBq of Flutemetamol was injected into the cubital vein. Time-of-flight algorithm including necessary corrections were applied to reconstruct the PET-images. Standard MRAC images were used to derive attenuation correction maps according standard implemented algorithms. Late frame (minutes 85–105) values were standardized by the cerebellar gray matter value (Vandenberghe et al., 2010), resulting in 3D-volumes of Flutemetamol retention as an estimate of β-amyloid burden via standard uptake value ratios (SUVR) (matrix=256×256×89, voxel size=1.2×1.2×2.78mm^3).

Single measures of individual cortical β-amyloid burden and iron-load were calculated for each participant based on average gray-matter ROI values of Flutemetamol-SUVR and susceptibility, respectively, as reported earlier (van Bergen et al., 2016b). To determine "amyloid-positive" status the Flutemetamol-SUVR cutoff value of 1.562 was used (Vandenberghe et al., 2010).

Assessment of SVCD by semi-automated WMH detection

To assess occurrence of WMH, each participant's FLAIR images were segmented into gray matter and white matter regions using the previously generated atlas. Parameters necessary for labeling atlas regions with WMH were determined by repeatedly manually optimizing the automated process. In a subset of 10 randomly selected participants all white matter regions exhibiting WMH were manually labeled to create a training dataset. Of the 110 white matter regions defined by the atlas, regions smaller than 1 ml were excluded as they were found to not be validly labeled by the automated process when optimizing the algorithm by comparison to manual assessment. This resulted in a total of 42 white matter regions where automated labeling was consistent with manual labeling in the training dataset (average corrected structure volume and standard deviation 5.17 ± 1.70 ml). All gray matter regions were grouped together to extract the average gray matter intensity per participant. As demonstrated earlier (Iorio et al., 2013), presence of WMH in each white matter region was automatically identified by counting voxels with intensities 1.5 standard deviation above the average gray matter intensity of each participant. Finally, regions including more than 0.25 ml of voxels identified as representing WMH, were labeled as exhibiting WMH. The threshold of 0.25 ml was determined by comparing manual with automated labeling for

maximizing specificity in the training dataset. Automated WMH assessment was finalized by manual validation of identified regions. This included adjustment of WMH counts when a region solely contained the edge of a single WMH while the core of that WMH was in another region. By summing the number of regions labeled as exhibiting WMH, a value indicating SVCD-burden was calculated for each participant.

Local correlation analysis

For each of the selected ROIs, WMH score and regional volume were used as outcome variables with local β-amyloid burden and local iron-load as predictors, while controlling for age and gender. All correlation analyses were performed using Spearman's rank correlation coefficient. To investigate differences in the correlation effects between oldest-old and younger-old, Fisher's r-to-z transformation was applied on the correlation coefficients within each region for each group (Fisher, 1921). False Discovery Rate (FDR) correction for multiple testing (Benjamini and Hochberg, 1995) was applied to the p-values of all regions for each predictor-outcome pair and results were found significant when p-FDR-corrected < 0.05. Two-sided t-tests were used for group comparisons. In case of non-normal distributed data, statistical tests for differences between groups were performed on log-transformed data. All statistical tests were performed in MATLAB R2016b (Mathworks, Natick, MA).

Results

Characteristics of the studied populations and neuropsychological performance

Demographic information for the investigated study populations and neuropsychological test performance at time of inclusion are summarized in table 1. The average education level, as measured by years of formal education, was significantly lower in oldest-old compared to younger-old (oldest-old: 14.2 (2.8) years; younger-old: 15.9 (2.6), p=0.010). Clinical examination revealed self-reliance and absence of cognitive impairment in the oldest-old group. However, they performed significantly lower than the younger-old group in all administered neuropsychological tests except CERAD word list recognition (table 1B). Eleven out of 36 younger-old (31%) and six out of 44 oldest-old (14%) were APOE4 carriers. Fisher test on the odds ratio of an APOE4 carrier having oldest-old status resulted in a non-significant trend (p=0.071, CI=0.11–1.09).

Prevalence of neuropathological burden in oldest- versus younger-old

While corrected structure volume in cortical gray matter regions and the hippocampus was significantly lower in oldest-old compared to younger-old, no significant difference could be observed for the entorhinal cortex (figure 1A, supplementary table 1A). The cutoff for Flutemetamol SUVR (Vandenberghe et al., 2010) identified eight oldest-old and five younger-old participants as "amyloid-positive". Consistently, quantitative assessment of Flutemetamol SUVR indicated significantly higher regional β-amyloid plaque burden in the oldest-old than younger-old for all twelve investigated brain structures (figure 1B, supplementary table 1B). Deep frontal white matter was found to have the lowest average susceptibility standard deviations and was selected as a reference region to assess relative iron-load for each participant. Interestingly, iron-load in the oldest-old was significantly lower in neocortical regions, insula and posterior cingulate. Only in the putamen was iron-

load higher in oldest-old than the younger-old (figure 2, supplementary table 1C). As SVCD-burden was non-normally distributed, group comparisons were performed on log-transformed scores. Almost all oldest-old exhibited substantial SVCD upon visual inspection, which is reflected by significantly higher (p=0.004) SVCD in oldest-old (6.59 ± 0.62) compared to younger-old (2.36 ± 0.29, supplementary table 1D). For assessment of effects accountable to age, a 1-way MANCOVA with age as covariate was used to compare neuropsychological test scores, volume, cortical β-amyloid burden, cortical iron and log-transformed SVCD-burden between oldest-old and younger-old. Here, no significant difference could be observed, when correcting for age.

Relationship between β-amyloid burden, iron-load, structure volume and prevalence of SVCD

Significant correlations (p-FDR-corrected<0.05) in the whole sample were found between β-amyloid burden and structure volume in the amygdala; and between iron-load and structure volume in insula, entorhinal cortex and parietal cortex (table 2A). Prevalence of SVCD correlated with β-amyloid burden in the entorhinal cortex and frontal cortex. Moreover, SVCD correlated negatively with iron-load in the amygdala, entorhinal cortex, parietal cortex and the neocortex as a whole (table 2B). When testing APOE4 carriers separately, significant correlations between β-amyloid burden and SVCD (p=0.01 r=0.80) and iron-load and volume (p=0.02 r=−0.60) could be observed in the entorhinal cortex.

Group-specific correlations of structure volume with β-amyloid burden

Secondary, group specific regression-analysis indicated a significant correlation of high local β-amyloid burden with high structure volume in the entorhinal cortex of the oldest-old, which was not present in the younger-old (figure 3, oldest-old p=0.01 r=0.39, younger-old p=0.59 r=−0.09) and insula (oldest-old p=0.04 r=0.31, younger-old p=0.31 r=−0.18), significant difference of correlations was confirmed by Fisher's r-to-z transformation (entorhinal cortex p=0.031, insula p=0.032).

To identify potential effects of education level, correlation analysis was performed with local structure volume and local β-amyloid burden as outcome variables and years of education as predictor, while controlling for age and gender. No significant correlation with years of education was found in any of the structures (supplementary table 2).

Discussion

By investigating a study population of cognitively unimpaired younger- and oldest-old by combined PET-MRI, we found significantly higher prevalence of neuropathological burden in the oldest-old, as reflected by cerebral β-amyloid burden, reduced volume of structures and higher prevalence of SVCD. While neuropsychological testing indicated generally lower performance levels in the oldest-old, they did not show significant cognitive impairment. Differences in the oldest-old furthermore included lower iron-load in cortical regions and an association of high entorhinal volume with entorhinal β-amyloid burden. Our findings support earlier considerations that distinct physiological brain properties may allow for maintained high cognitive functioning in the oldest-old, despite present brain pathology

(Barulli and Stern, 2013; Nyberg et al., 2012). To our knowledge, this is the first report indicating that reduced QSM measures of cortical iron-load constitute a lower vulnerability to loss of cognitive function at highest age.

Amyloid-PET tracers, such as 18F-Flutemetamol (Vandenberghe et al., 2010), have become an established approach to estimate regional β-amyloid burden in AD-risk populations. Differences in brain structure volumes were investigated by applying a multi-atlas matching approach to T1-MRI data, using Likelihood Fusion and Ontology Level Control algorithms, as validated for both healthy and diseased study populations (Djamanakova et al., 2014; Tang et al., 2013). Recent efforts in validation of the QSM technology made it possible to quantitatively assess regional iron-load in vivo (Deistung et al., 2013; Langkammer et al., 2012) and assess iron in a context of neurodegenerative disease (Acosta-Cabronero et al., 2013; Ayton et al., 2017; van Bergen et al., 2016a; van Bergen et al., 2016b). When interpreting the susceptibility data, it needs to be considered that the iron-load could vary on an inter-voxel basis and that QSM is biased by decreased myelin density (Langkammer et al., 2012; Liu et al., 2011). However, the cortical and deep gray matter regions investigated in this study are low in myelin content and thus the myelin contribution was considered minimal. Distortion by processes of co-registration of PET with MR-indicators of neuropathological burden or bias due to changes occurring in the time between PET and MR acquisition could be avoided as the respective measures were acquired using an integrated PET-MR instrument.

When investigating the entire study sample, a significant relationship between β-amyloid burden and reduced volume resulted, which appears consistent with earlier reports on biomarker-associations in populations of older adults at risk for AD (Frisoni et al., 2010; Mormino et al., 2014). Our observation of SVCD correlating with β-amyloid burden concurs with earlier ADNI-findings (Guzman et al., 2013). Interestingly, we find negative correlations between iron and SVCD throughout the brain - which surprised us, as we expected SVCD to be associated with paramagnetic properties due to extravasated hemoglobin and vascular pathology. Our SVCD measure did not include the size but only the occurrence of WMH as a reflection of incidence of vascular breakdown. As we cannot exclude that an analysis focused on WMH-size may provide different results, at this point our findings on SVCD in a context of iron need to be interpreted with caution. Additional studies are needed to validate the use of the here-applied WMH score for assessing SVCD, and also should allow for potential roles of activated microglia and iron clearing mechanisms. Our finding of substantial neuropathological burden in the oldest-old is consistent with earlier studies on high aged populations (Kawas et al., 2013). In general, reduced structural volume and increased β-amyloid burden were more pronounced in the oldest-old than in the younger-old, in line with earlier findings of reduced volume as an indicator of incipient neurodegeneration and cognitive decline (Dekhtyar et al., 2017; Frisoni et al., 2010; Mormino et al., 2014). The oldest-old population in our study showed a generally lower cognitive performance than the younger-old, which appears consistent with earlier reports on non-pathological cognitive change during aging. Oldest-old status in our sample was associated with fewer years of formal education, which reflects the lower availability of higher-education in Switzerland during adolescence of the very old participants. It is not expected that formal education influence results at this stage of their

life, this is supported by the lack of correlation between years of education and β-amyloid burden or structure volume. Additionally, we only found a non-significant trend regarding the effect of APOE4 status for the odds of being oldest-old versus younger-old. This finding could be due to insufficient power in our sample. Alternatively, it might be consistent with earlier reports that suggest other factors of brain physiology beyond APOE4 determine cognitive functioning at a very high age (Corrada et al., 2013; Garibotto et al., 2012). The fact that our oldest-old population exhibited a high degree of cognitive functionality despite present neuropathology concurs with earlier observations of preserved cognition at highest age (Nyberg et al., 2012; Rogalski et al., 2013). Considering the well-established relationship between high β-amyloid burden and risk for cognitive decline during aging (Jansen et al., 2015), our finding of significantly higher β-amyloid burden in cognitively unimpaired oldest-old participants suggests particular resilience against neuropathology. Here, our findings of lower iron-load in brain regions implicated in cognitive processes, such as the neocortex, posterior cingulate and insula, potentially reflect less neuronal damage. Pathological processes that are considered to be reflected by increased local iron-load include oxidative stress and presence of activated microglia (Meadowcroft et al., 2009; Nunez et al., 2012; Rottkamp et al., 2001; Serrano-Pozo et al., 2016; Zeineh et al., 2015). Moreover, increased iron-load is a frequent finding in neurodegenerative disease (Andersen et al., 2014; Kruer, 2013). Increased iron-load in basal ganglia structures, particularly the putamen, are a known effect of aging (Bartzokis et al., 1997; Hallgren and Sourander, 1958) and are consistent with the spatial distribution of our QSM measures of local iron-load. Our observation of low cortical iron-load in the cognitively unimpaired oldest-old might thus reflect lower vulnerability to age-related neuropathology, and may be consistent with reports of elevated brain iron being associated with mild cognitive impairment and liability for AD (Ayton et al., 2015; Ayton et al., 2017; Derry and Kent, 2017; van Bergen et al., 2016b). Furthermore, our findings are consistent with recently published data on a relationship between increased QSM measures of cerebral iron and β-amyloid associated cognitive decline (Ayton et al., 2017).

Several studies have investigated changes to the entorhinal cortex associated with aging and incipient AD, as indicated by reduced structural volume (de Leon et al., 1989; Frisoni et al., 2010), and found that increased structural volume of memory regions promotes maintained cognitive performance (Dekhtyar et al., 2017; deToledo-Morrell et al., 2004). Thus, while the current clinical study does not provide information on neurobiological mechanisms, the here reported positive relationship between entorhinal structural volume and β-amyloid plaque-density, which was only observable in the oldest-old, might indicate lower vulnerability. However, as entorhinal cortex volumes in the oldest-old did not differ from the younger-old, this finding needs to be interpreted with caution.

Taken together, by investigating a cross-sectional sample of younger- and oldest-old, we provide neuroimaging-evidence that low cortical iron-load and high entorhinal volume despite high β-amyloid burden might characterize individuals less affected by aging-associated neuropathologies. Additional translational studies are needed to characterize the interplay between molecular mechanisms and genetic disposition that allows for maintained cognitive function at highest age. While our findings are consistent with recent reports on low iron burden as a predictor of preserved cognitive functioning in older adults (Ayton et

al., 2017), therapeutic trials are needed to investigate whether these correlates of individual resilience may be exploited for specific disease modifying intervention.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

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Abbreviations

FLAIR	Fluid-attenuated inversion recovery
QSM	Quantitative susceptibility mapping
SVCD	small-vessel cerebrovascular disease
WMH	White matter hyperintensities

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Highlights

- Combined PET-MRI was used to investigate maintained cognition at highest age
- QSM measures of cortical iron load were lower in cognitively unimpaired oldest-old
- Low cortical iron constitutes low vulnerability to aging-associated neuropathologies
- In the oldest-old, high entorhinal cortex volume was associated with high β-Amyloid

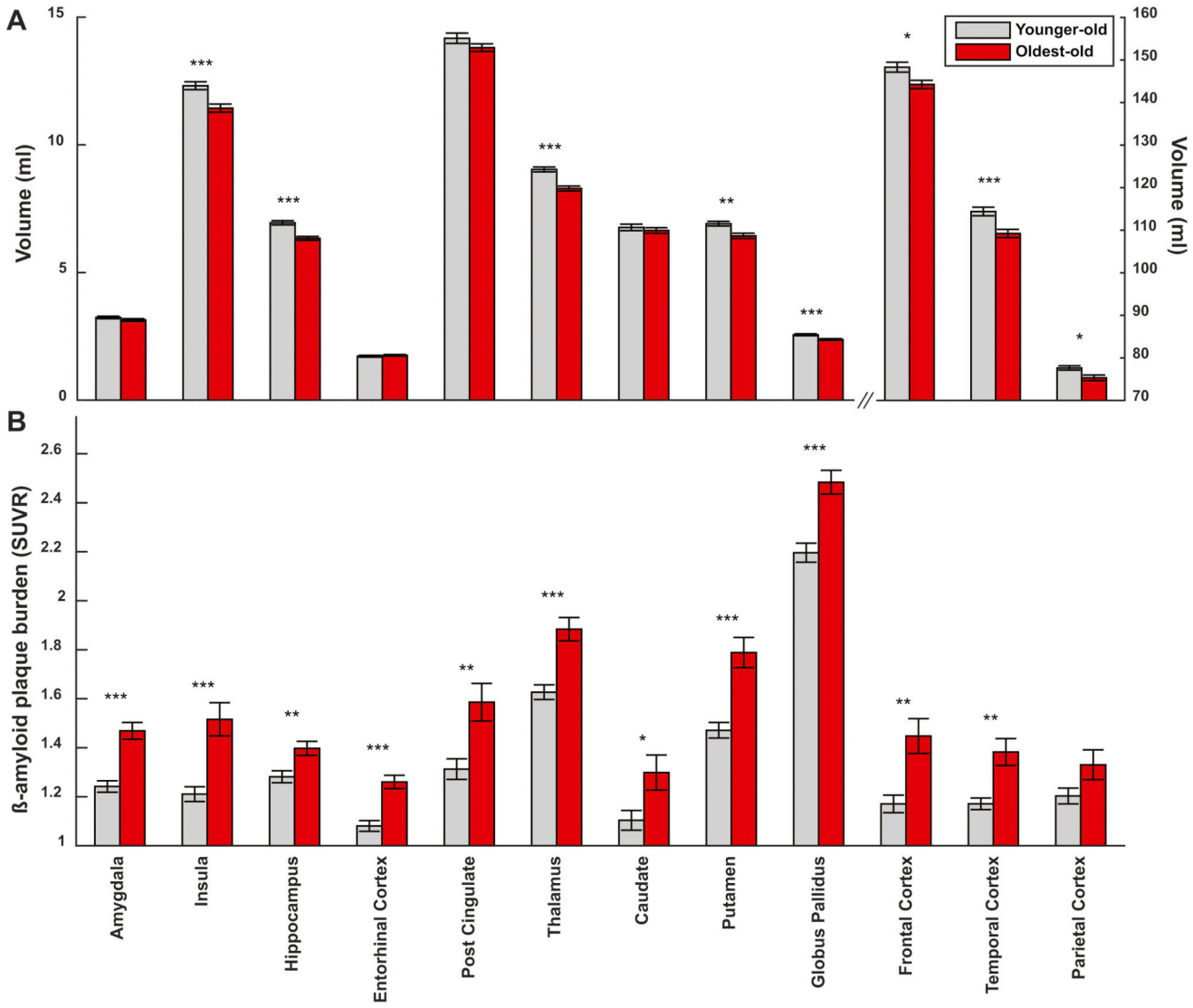

Figure 1.

Mean regional average values (SEM) per group for **A)** volume (ml), **B)** β-amyloid plaque burden (18F-Flutemetamol SUVR). Significant differences after FDR-multiple-testing-correction are indicated by * = $p < 0.05$, ** = $p < 0.01$ and *** = $p < 0.001$.

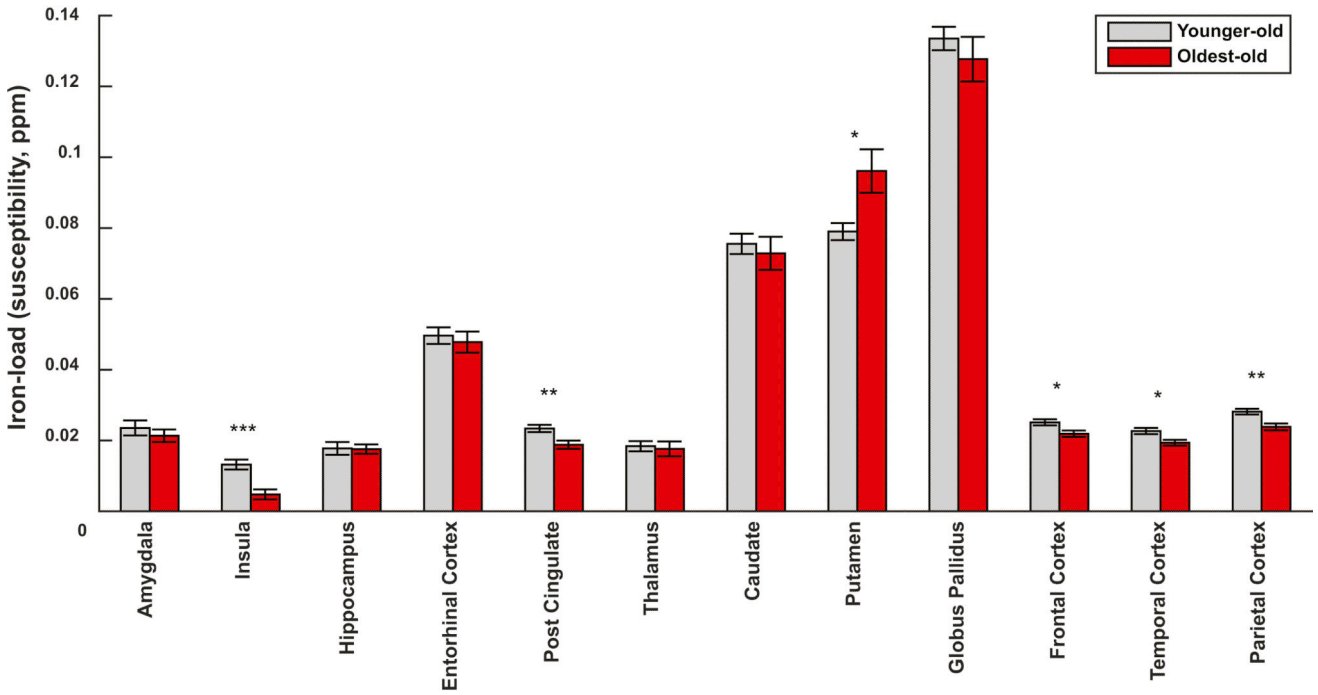

Figure 2.

Mean regional average values (SEM) per group for iron (susceptibility, ppm). Significant differences after FDR multiple testing correction are indicated by * = $p < 0.05$, ** = $p < 0.01$ and *** = $p < 0.001$.

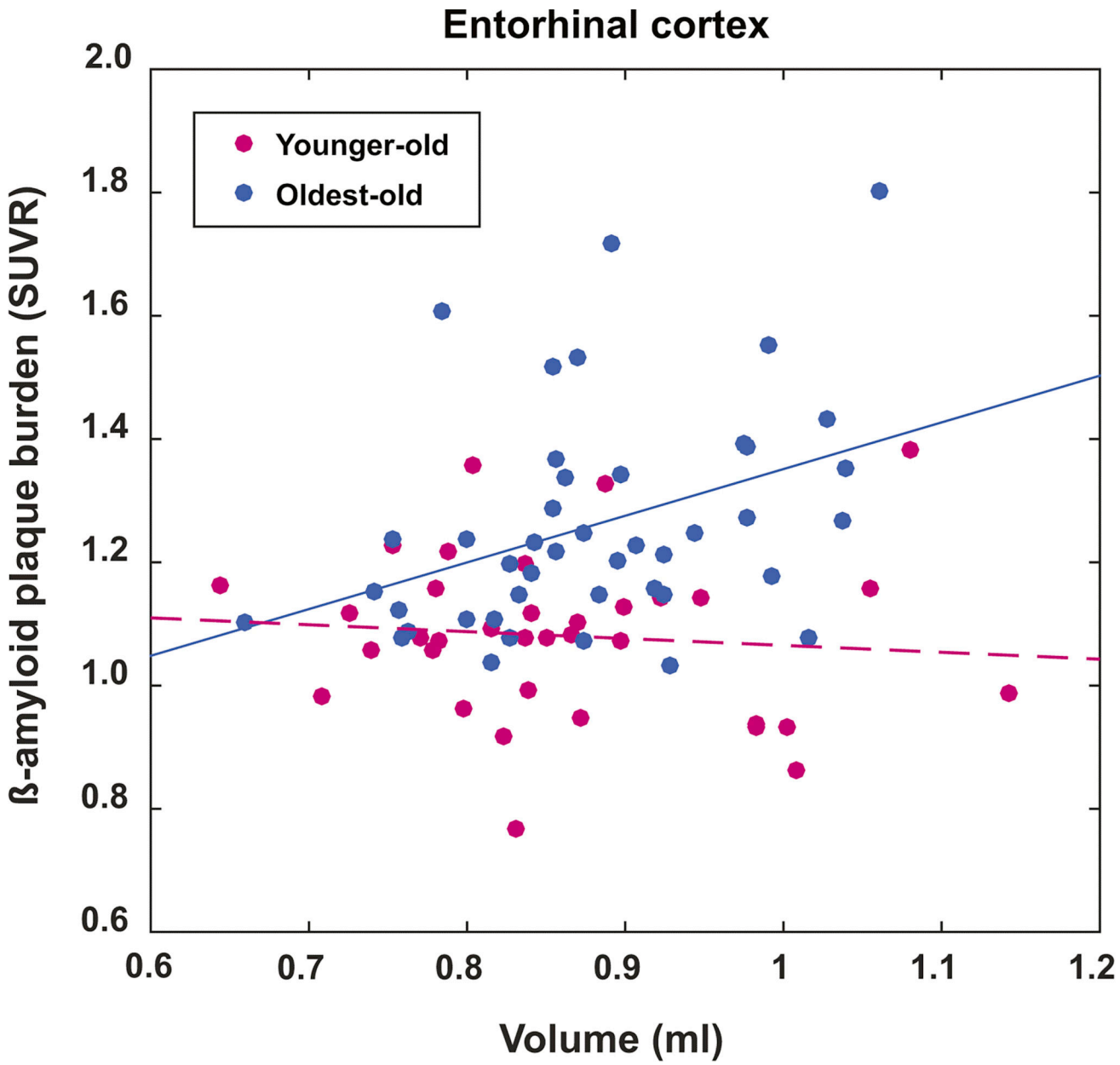

Figure 3.
Scatterplot for correlations between entorhinal volume (ml) and entorhinal β-amyloid plaque burden for oldest-old (r=0.39, p=0.01), younger-old r=−0.09, p=0.59.

Table 1

Overview of sample A) demographics and B) neuropsychological test performance measures as mean ± STD.

	Whole sample	Younger-old	Oldest-old
A) Demographics			
N (M/F)	80 (54/26)	36 (21/15)	44 (33/11)
Age	79.20 ± 11.80	67.75 ± 7.75	88.57 ± 2.69 **
Education	14.99 ± 2.85	15.92 ± 2.61	14.23 ± 2.84 **
ApoE-e4 carriers (%)	17 (21%)	11 (31%)	6 (14%)
B) Neuropsychology			
MMSE	28.99 ± 1.10	29.44 ± 0.81	28.60 ± 1.17 **
VLMT: delayed recall	7.93 ± 3.99	8.58 ± 3.93	7.43 ± 4.02 **
Boston Naming Test	14.43 ± 0.77	14.73 ± 0.45	14.21 ± 0.89 **
Trail making test B/A	2.61 ± 1.41	2.17 ± 0.70	2.98 ± 1.71 **
CERAD: Word list recall	6.99 ± 1.93	7.79 ± 1.32	6.36 ± 2.12 **
CERAD: Word list recognition	9.77 ± 0.65	9.76 ± 0.61	9.78 ± 0.69
CERAD: Word list learning	8.23 ± 1.39	8.82 ± 0.98	7.76 ± 1.49 **
CERAD: Fluency	21.54 ± 6.91	24.36 ± 5.61	19.37 ± 7.08 **
Stroop Interference: color-word	32.60 ± 11.26	27.91 ± 7.50	36.48 ± 12.40 **

* = significant difference (two-sample T-test) between the oldest-old and younger-old with $p < 0.05$,

** = $p < 0.01$ and

*** = $p < 0.001$.

Table 2

Regional correlation analysis for A) volume and B) SVCD with the respective local β-amyloid plaque burden and iron-load. Indicated are values for the entire sample (n=80)

	Statistics, correlation analysis	
	β-amyloid plaque burden	***Iron-load***
A) Regional volume		
Amygdala	p=0.01 r=0.28 *	p=0.94 r=−0.03
Insula	p=0.99 r=0.00 †	p=0.02 r=0.28 *
Hippocampus	p=0.55 r=−0.08	p=0.74 r=0.06
Entorhinal Cortex	p=0.08 r=0.21 †	p=0.01 r=−0.30 *
Frontal Cortex	p=0.99 r=0.00	p=0.54 r=0.09
Temporal Cortex	p=0.34 r=0.12	p=0.10 r=0.19
Parietal Cortex	p=0.18 r=−0.16	p=0.03 r=0.26 *
Occipital Cortex	p=0.99 r=−0.02	p=0.68 r=0.06
Neocortex	p=0.90 r=−0.04	p=0.11 r=0.19
B) SVCD-burden (WMH-scores)		
Amygdala	p=0.06 r=0.22	p=0.07 r=−0.22
Insula	p=0.07 r=0.22	p=0.42 r=−0.12
Hippocampus	p=0.99 r=0.01	p=0.98 r=0.04
Entorhinal Cortex	p=0.05 r=0.23 *	p=0.05 r=−0.24 *
Frontal Cortex	p=0.05 r=0.23 *	p=0.06 r=−0.23
Temporal Cortex	p=0.17 r=0.17	p=0.03 r=−0.26 *
Parietal Cortex	p=0.23 r=0.16	p=0.01 r=−0.29 *
Occipital Cortex	p=0.48 r=0.11	p=0.12 r=−0.19
Neocortex	p=0.11 r=0.20	p=0.03 r=−0.26 *

* indicates a significant correlation with p-FDR-corrected < 0.05;

† = significant differences in regressions slopes between oldest-old and younger-old using Fisher r-to-z transformation, with p < 0.05.