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RESEARCH ARTICLE

# Amyloid-Related Memory Decline in Preclinical Alzheimer's Disease Is Dependent on *APOE* $\epsilon$ 4 and Is Detectable over 18-Months

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## Abstract

High levels of  $\beta$ -amyloid ( $A\beta$ ) in the brain and carriage of the *APOE*  $\epsilon$ 4 allele have each been linked to cognitive impairment in cognitively normal (CN) older adults. However, the relationship between these two biomarkers and cognitive decline is unclear. The aim of this study was to investigate the relationship between cerebral  $A\beta$  level, *APOE*  $\epsilon$ 4 carrier status, and cognitive decline over 18 months, in 317 cognitively healthy (CN) older adults (47.6% males, 52.4% females) aged between 60 and 89 years (Mean = 69.9, SD = 6.8). Cognition was assessed using the Cogstate Brief Battery (CBB) and the California Verbal Learning Test, Second Edition (CVLT-II). Planned comparisons indicated that CN older adults with high  $A\beta$  who were also *APOE*  $\epsilon$ 4 carriers demonstrated the most pronounced decline in learning and working memory. In CN older adults who were *APOE*  $\epsilon$ 4 non-carriers, high  $A\beta$  was unrelated to cognitive decline in learning and working memory. Carriage of *APOE*  $\epsilon$ 4 in CN older adults with low  $A\beta$  was associated with a significantly increased rate of decline in learning and unexpectedly, improved cognitive performance on measures of verbal episodic memory over 18 months. These results suggest that  $A\beta$  and *APOE*  $\epsilon$ 4 interact to increase the rate of cognitive decline in CN older adults and provide further support for the use of  $A\beta$  and *APOE*  $\epsilon$ 4 as biomarkers of early Alzheimer's disease.

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## Introduction

In cognitively normal (CN) older adults, both an abnormal level of amyloid- $\beta$  ( $A\beta$ ) and carriage of the apolipoprotein E (*APOE*)  $\epsilon 4$  allele have been identified as risk factors for cognitive decline and the development of Alzheimer's disease (AD) [1–4]. The amyloid cascade model of AD posits that  $A\beta$  accumulation gives rise to neurodegeneration, loss of neurotransmitter function, and ultimately, cognitive impairment and dementia [5,6]. While *APOE*  $\epsilon 4$  influences cell death through promoting the toxic effects of  $A\beta$ , it also contributes to AD pathogenesis indirectly by reducing synaptic plasticity and increasing risk for cerebrovascular events and/or mitochondrial dysfunction [7–11]. *In vitro* studies also indicate that the effects of  $A\beta$  and *APOE*  $\epsilon 4$  can interact to promote cell death [12–14]. The results of recent clinical studies in humans also support the hypothesis that *APOE*  $\epsilon 4$  and  $A\beta$  interact to influence AD disease progression. Specifically, while the deleterious effects of  $A\beta$  on cognitive function, particularly in episodic memory, in CN adults was well known [15–17], the magnitude of  $A\beta$  related decline in episodic memory over 36–54 months in  $A\beta$ + CN adults was increased further in individuals who carried the *APOE*  $\epsilon 4$  allele [18–20]. However, interactions between  $\epsilon 4$  and  $A\beta$  related cognitive decline in CN adults have not been observed when studies have been restricted to periods of 18 months [15,16]. Taken together, these data suggest that while  $\epsilon 4$  does exacerbate  $A\beta$  related cognitive decline in CNs, this interaction may only become evident over longer periods of assessment.

Understanding how *APOE*  $\epsilon 4$  moderates  $A\beta$  toxicity in CN adults provides an exciting opportunity for the development of anti- $A\beta$  therapies based on the protective actions of the apoE2 and apoE3 isoforms [10,21]. If this were the case, such therapies could be described as alleviating, or even curing, the effects of *APOE*  $\epsilon 4$ . Given the accepted importance of this lipoprotein in epidemiological and experimental models of AD [21,22], such statements would most likely be accepted as being reflective of effects that are clinically important. Furthermore, as clinical trials of drugs designed to reduce  $A\beta$  toxicity are typically conducted over intervals of 18-months [23,24], it is important to determine whether the  $\epsilon 4$  exacerbation of  $A\beta$  related cognitive decline requires more than 18 months to become evident, or whether the absence of such effects in studies of this duration was related to the relatively small sample sizes studied did not provide sufficient statistical power to detect the interaction of apoE4 and amyloid on memory.

The aim of the current study was to characterize *APOE*  $\epsilon 4$ -related acceleration of  $A\beta$ -related cognitive decline over an 18-month test-retest interval on a computerized cognitive battery in a large group of CN older adults whose  $\epsilon 4$  and  $A\beta$  status was known. The hypothesis was that in CN older adults, cognitive decline over 18 months would be greatest in those who were  $A\beta$ + and  $\epsilon 4$  carriers.

## Materials and Methods

CN older adults ( $n=317$ ) enrolled in the Australian Imaging, Biomarkers and Lifestyle (AIBL) study who had undergone positron emission tomography (PET) neuroimaging for  $A\beta$  and who had completed cognitive assessments at a baseline and 18 month assessment participated in this study. The process of recruitment and diagnostic classification of CN older adults has been described previously [25]. Participants were excluded from the study if they had any of the following: schizophrenia, depression (15-item Geriatric Depression Scale [GDS] score  $\geq 6$ ), Parkinson's disease, cancer (other than basal cell skin carcinoma) within the last two years, obstructive sleep apnoea, symptomatic stroke, uncontrolled diabetes, or current regular alcohol use exceeding two standard drinks per day for women or four per day for men. Demographic data including age, sex, education level was collected and scores for premorbid

**Table 1. Demographic and clinical characteristics.**

	Overall	A $\beta$ - $\epsilon 4$ non-carriers	A $\beta$ - $\epsilon 4$ carriers	A $\beta$ + $\epsilon 4$ non-carriers	A $\beta$ + $\epsilon 4$ carriers
N	317	182	59	31	45
N (%) female	166 (52.4%)	93 (51.1%)	32 (54.2%)	17 (54.8%)	24 (53.3%)
N (%) high A $\beta$ +	40 (12.6%)	n/a	n/a	14 (45.2%)	26 (57.8%)
Age, mean (SD)	69.9 (6.8)	68.8 (6.0)	66.5 (4.9)	76.0 (7.2)	72.3 (7.1)
Education (years)	13-15	13-15	15+	13-15	13-15
Premorbid IQ, mean (SD)	108.58 (7.02)	108.46 (6.87)	107.36 (7.83)	111.28 (6.22)	108.89 (6.34)
GDS*, mean (SD)	0.84 (1.31)	0.90 (1.39)	1.02 (1.51)	0.48 (0.87)	0.62 (0.89)
HADS-D <sup>@</sup> , mean (SD)	2.61 (2.51)	2.59 (2.31)	2.73 (2.01)	1.83 (1.49)	2.98 (2.76)
HADS-A <sup>#</sup> , mean (SD)	4.20 (2.80)	4.24 (2.75)	4.02 (2.84)	3.07 (2.00)	5.13 (3.29)
CDR-SB <sup>§</sup> , mean (SD)	0.43 (0.17)	0.04 (0.15)	0.05 (0.14)	0.07 (0.18)	0.02 (0.10)
MMSE <sup>^</sup> , mean (SD)	28.87 (1.19)	28.90 (1.20)	28.82 (1.24)	28.79 (1.24)	28.71 (1.16)

\*GDS = Geriatric Depression Scale

@HADS-D = Hospital Anxiety and Depression Scale, Depression Subscale

#HADS-A = Hospital Anxiety and Depression Scale, Anxiety Subscale

§CDR-SB = Clinical Dementia Rating scale, Sum of Boxes score

^MMSE = Mini Mental State Examination

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IQ, and depressive and anxiety symptoms (using the GDS and the Hospital Anxiety and Depression Scale) were also collected at screening (see Table 1). The study was approved by and complied with the regulations of the institutional research and ethics committees of Austin Health, St. Vincent's Health, Hollywood Private Hospital and Edith Cowan University [25]. All participants provided written informed consent prior to being tested.

A $\beta$  PET imaging was conducted using either <sup>11</sup>C-Pittsburg-compound B (<sup>11</sup>C-PiB), <sup>18</sup>F-florbetapir, or <sup>18</sup>F-flutemetamol. A 30-minute acquisition was started 40-minutes post-injection of PiB, a 20-minute acquisition was performed 50-minutes post-injection of florbetapir and 90-minutes post-injection of flutemetamol. For PiB-PET, standardized uptake value (SUV) data were summed and normalized to the cerebellar cortex SUV, resulting in a region-to-cerebellar ratio termed SUV ratio (SUVR). The whole cerebellum was the reference region for florbetapir, while for flutemetamol, the reference region was the pons. High A $\beta$  was classified as SUVR  $\geq 1.5$  for <sup>11</sup>C-PiB, SUVR  $\geq 1.1$  for <sup>18</sup>F-florbetapir, and SUVR  $\geq 0.62$  for <sup>18</sup>F-flutemetamol. A $\beta$ + levels were further classified as being "high" A $\beta$ + (SUVR PiB  $> 1.9$ ; flutemetamol  $> 0.82$ ; florbetapir  $> 1.29$ ) or "low" A $\beta$ + (SUVR PiB = 1.5-1.9; flutemetamol = 0.62-0.82; florbetapir = 1.11-1.29) [26,27]. 80ml fasted blood samples were collected from each participant, of which 0.5 ml was sent to a clinical pathology laboratory for APOE genotyping.

Cognition was assessed using the CVLT-II (immediate and delayed recall scores) and the Cogstate Brief Battery (CBB) because these measures have demonstrated sensitivity to cognitive impairment in mild cognitive impairment (MCI) and AD and to cognitive decline associated with A $\beta$ + in preclinical AD [15,28]. The CVLT-II involves participants learning a 16-item word list over five trials. The CBB consists of four computerised card games that measure cognitive performance across four domains: psychomotor function, visual attention, working memory, and learning. The Detection task (DET) assesses psychomotor function. During the task, a card is presented face down in the centre of the computer screen and when the card turns face up, participants are required to press the yes button as quickly as possible. Psychomotor function was assessed by measuring the time (milliseconds) taken to respond correctly, which was normalized using a logarithmic base 10 ( $\log_{10}$ ) transformation. The Identification

task (IDN) assesses visual attention. During the task, participants respond to the question “is the card red?” using yes and no buttons. Visual attention was assessed by measuring the time (milliseconds) taken to respond correctly, which was normalized using a  $\log_{10}$  transformation. The One Card Learning task (OCL) assesses learning. During the task, participants use yes and no buttons to respond to the question “have you seen this card before in this task?” as cards are presented. During the task, six playing cards are repeatedly displayed amongst distractors (non-repeating cards). Learning was assessed by measuring the accuracy of participant response, which was quantified as the proportion of correct trials during the task, and normalized using an arcsine square-root transformation. The One Back task (OBK) assesses working memory. During the task, participants use yes and no buttons to respond to the question “is the previous card the same?” Working memory was assessed by measuring the accuracy of participant responses, which was quantified as the proportion of correct trials during the task, and normalized using an arcsine square-root transformation. Two composite scores were also constructed from these measures, a Psychomotor/Attention (DETIDN) composite, and a Learning/Working Memory (OCLOBK) composite. Data for ratings on the Mini Mental State Examination (MMSE) and the Clinical Dementia Rating (CDR) scale were also collected for the baseline and 18 month assessments.

## Data Analysis

Data for each cognitive outcome measure was analysed using a series of pairwise comparisons ( $df=3$ ) conducted within an analysis of covariance (ANCOVA). These comparisons were set to reflect the hypotheses that compared to  $A\beta^- \epsilon 4$  non-carriers, cognitive decline would be greatest in  $A\beta^+ \epsilon 4$  carriers. In each ANCOVA,  $A\beta$  and  $APOE$  carrier status were entered as fixed factors, and age, premorbid IQ, levels of anxiety symptoms, and the baseline measure of the task were entered as covariates (as these were found to differ between groups [Table 1](#)). The 18-month scores for each measure were entered as the dependent variable. The magnitude of difference for change in cognitive performance over 18 months from the  $A\beta^- \epsilon 4$  non-carrier group was calculated for each group using the estimated marginal means at 18 months and differences between groups were expressed using Cohen's  $d$  and 95% confidence intervals (95% CIs).

## Results

### Demographic and clinical characteristics

Demographic and clinical characteristics for the overall sample and each  $A\beta/APOE$  group are shown in [Table 1](#). Differences between groups were identified for age [ $F(3,313) = 17.81$ ,  $p < .001$ ], premorbid IQ [ $F(3,312) = 2.96$ ,  $p = .03$ ] and levels of anxiety symptoms [ $F(3,311) = 3.05$ ,  $p = .03$ ]. Groups did not differ on any other clinical or demographic characteristic (all  $p$ 's  $> .05$ ). Consequently, age, premorbid IQ and levels of anxiety symptoms were included as covariates in comparisons of cognitive performance between groups. There were no differences in the proportion of  $\epsilon 4$  carriers or non-carriers who were classified as high  $A\beta^+$ ,  $\chi^2 = 1.17$ ,  $p = .28$  ([Table 1](#)).

### Effect of $A\beta$ and $APOE \epsilon 4$ on cognitive decline over 18 months

Baseline- and covariate-adjusted means for the 18-month assessment are shown in [Table 2](#), and the magnitude of difference between groups is shown in [Fig 1](#). In the  $A\beta^-$  groups, no differences between  $\epsilon 4$  carriers and non-carriers were observed for any of the cognitive measures. Compared to  $A\beta^- \epsilon 4$  non-carriers,  $A\beta^- \epsilon 4$  carriers showed a slight improvement on the

CVLT-II immediate total recall at 18 months, and no decline on any other cognitive measure. In contrast, compared to  $A\beta^- \epsilon 4$  non-carriers,  $A\beta^+ \epsilon 4$  carriers performed significantly worse at 18 months on the OCL, OBK and the OCLOBK composite scores, with each of these differences between groups moderate in magnitude (Table 2).

### Discussion

The results of this study support the hypothesis that in CN older adults, cognitive decline over 18 months is greatest in  $A\beta^+$  CN older adults who were  $\epsilon 4$  carriers. In fact, the only statistically significant cognitive decline identified in the current study was between  $A\beta^+ \epsilon 4$  carriers and  $A\beta^- \epsilon 4$  non-carriers (Table 2). This group showed a decline over 18 months, that was moderate in magnitude, on measures of visual learning (Cogstate OCL task), working memory (Cogstate OBK Task) and a learning/working memory composite score (OCLOBK; Table 2).  $A\beta^+ \epsilon 4$  carriers also showed decline on the measure of verbal delayed recall but the magnitude of this was not sufficient to reach statistical significance (Table 2). In contrast, both  $A\beta^+ \epsilon 4$  non-carriers and  $A\beta^- \epsilon 4$  carriers showed no decline over the 18 months for any aspect of cognitive function measured (Table 2). Interestingly,  $A\beta^- \epsilon 4$  carriers showed a decline of a moderate magnitude over 18 months, but only for the measure of visual learning and this decline was not sufficient to reach statistical significance. Considered together, these data in general suggest that in CN older adults, memory decline over relatively short intervals requires the additive effects of  $A\beta^+$  and  $APOE \epsilon 4$ . These results are largely consistent with recent studies conducted over 36-54 months which demonstrated that  $A\beta$  related decline in memory was much greater if individuals also were  $APOE \epsilon 4$  carriers [18,19].

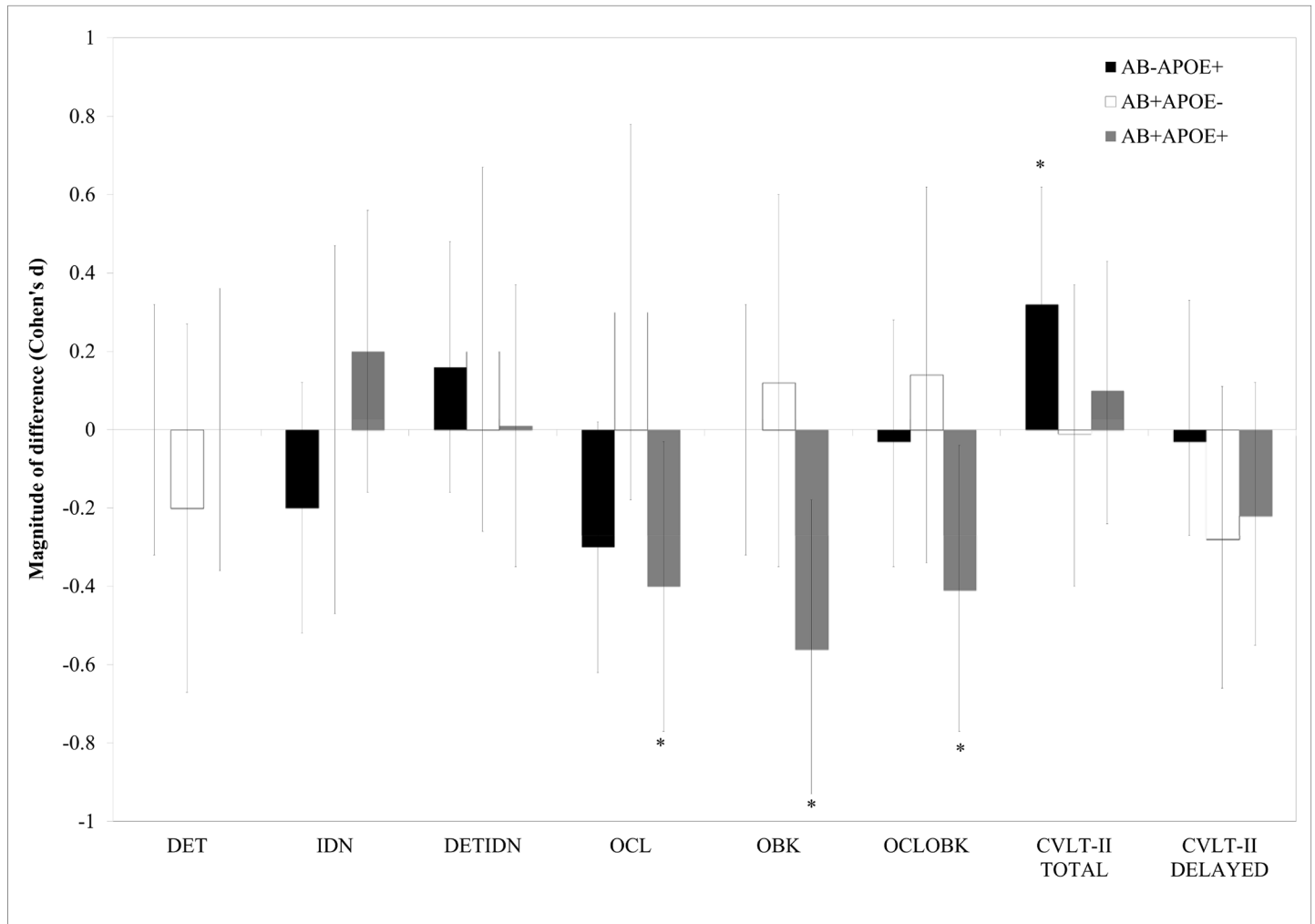
The findings of the current study therefore suggest that acceleration of  $A\beta^+$  related memory decline is evident in carriers of the  $APOE \epsilon 4$  allele and is sufficiently large enough to be evident over relatively short time periods. As such, it would be prudent for clinical trials of putative disease modifying drugs to stratify their  $A\beta^+$  samples according to  $APOE \epsilon 4$  status when memory

**Table 2. Baseline and covariate adjusted mean scores at 18 months for each group and Cohen's d of the difference in mean score change over 18 months, relative to the  $A\beta^- \epsilon 4$  non-carrier group.** Abbreviations: DETIDN, Psychomotor/Attention composite; DET, Detection task; IDN, Identification task; OCLOBK, Learning/Working Memory composite; OCL, One Card Learning task; OBK, One Back Learning task; CVLT-II Total, California Verbal Learning Test, Second Edition, total recall; CVLT-II Delay, CVLT-II, 20 minute delayed recall. NOTE. Bolded values are significant at the  $p < .05$  level. Means are adjusted for age, premorbid IQ, levels of anxiety symptoms, and baseline performance.

Task	18-month adjusted Mean (SD)				Cohen's d (95% CI) (vs. $A\beta^- \epsilon 4$ non-carriers)		
	$A\beta^- \epsilon 4$ non-carriers	$A\beta^- \epsilon 4$ carriers	$A\beta^+ \epsilon 4$ non-carriers	$A\beta^+ \epsilon 4$ carriers	$A\beta^- \epsilon 4$ carriers	$A\beta^+ \epsilon 4$ non-carriers	$A\beta^+ \epsilon 4$ carriers
DETIDN	-0.03 (0.68)	0.08 (0.70)	0.11 (0.71)	-0.02 (0.70)	0.16 [-0.16, 0.48]	0.20 [-0.26, 0.67]	0.01 [-0.35, 0.37]
DET	2.52 (0.10)	2.52 (0.10)	2.50 (0.10)	2.52 (0.10)	0.00 [-0.52, 0.12]	-0.20 [-0.67, 0.27]	0.00 [-0.36, 0.36]
IDN	2.71 (0.05)	2.70 (0.05)	2.71 (0.05)	2.72 (0.05)	-0.20 [-0.52, 0.12]	0.00 [-0.47, 0.47]	0.20 [-0.16, 0.56]
OCLOBK	0.07 (0.93)	0.04 (0.94)	0.20 (0.96)	-0.31 (0.95)	-0.03 [-0.35, 0.28]	0.14 [-0.34, 0.62]	<b>-0.41 [-0.77, -0.04]</b>
OCL	1.03 (0.10)	1.00 (0.10)	1.06 (0.10)	0.99 (0.10)	-0.30 [-0.62, 0.02]	0.30 [-0.18, 0.78]	<b>-0.40 [-0.77, -0.03]</b>
OBK	1.34 (0.16)	1.34 (0.16)	1.36 (0.17)	1.25 (0.17)	0.00 [-0.32, 0.32]	0.12 [-0.35, 0.60]	<b>-0.56 [-0.93, -0.18]</b>
CVLT-II Total	49.58 (7.54)	52.01 (7.68)	49.47 (7.94)	50.31 (7.64)	<b>0.32 [0.02, 0.62]</b>	-0.01 [-0.40, 0.37]	0.10 [-0.24, 0.43]
CVLT-II Delay	11.83 (2.57)	11.91 (2.62)	11.11 (2.71)	11.27 (2.61)	0.03 [-0.27, 0.33]	-0.28 [-0.66, 0.11]	-0.22 [-0.55, 0.12]

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**Fig 1. Magnitude of difference for cognitive decline over 18 months, relative to the Aβ- ε4 non-carrier group.** 0 line represents the Aβ- ε4 non-carrier group; error bars represent 95% confidence intervals. \* $p < .05$ .

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measures are included as the endpoint. The data from this study can also be used as a foundation for computation of statistical power calculations that may be relevant to the design of clinical trials for early AD. For example, using the data presented in Table 2, the extent to which  $\epsilon 4$  increased Aβ related memory decline is moderate in magnitude (i.e., Aβ+  $\epsilon 4$  non-carriers vs. Aβ+  $\epsilon 4$  carriers  $d = 0.53$ ). As such, the sample size required to detect a therapeutic effect of alleviating the effects of  $\epsilon 4$  would be 57 per group (assuming  $d = 0.53$ ,  $\alpha = 0.05$ , power = 0.80, two-tailed distribution, and equal sample size in both groups).

The absence of any cognitive decline in Aβ+  $\epsilon 4$  non-carriers in the current study suggests that, by itself Aβ+ was not sufficient for the manifestation of cognitive decline in CN older adults. Similarly, when CN older adults were followed over much longer periods (e.g., 4.5 years), Aβ+  $\epsilon 4$  non-carriers also showed very little decline in memory or other aspects of cognitive function [18,19]. These data are now becoming strong enough to suggest a revision for the current pathological models of AD which propose that in the preclinical stage of the disease, Aβ+ by itself is the necessary condition for cognitive decline [29,30]. However, few studies have stratified their Aβ+ CN older groups according to APOE  $\epsilon 4$  status because the number of



CN  $\epsilon 4$  carriers present in preclinical AD samples has been relatively small and therefore studies have been unable to directly test these pathological models of AD. Given the current findings and their consistency with previous data gathered over longer time intervals it is possible that the  $A\beta$  related cognitive decline reported in CN older adults is being driven also by the additive effects of the *APOE*  $\epsilon 4$  allele [18,19]. The current findings also suggest that current models of AD need to consider the effect of genetic polymorphisms in moderating the rate by which neuropathological processes occur.

The current study found that, in the absence of  $A\beta+$ , *APOE*  $\epsilon 4$  also had no effect on cognitive function. The two previous studies that examined the extent to which  $A\beta+$  and *APOE*  $\epsilon 4$  influenced cognitive decline also observed no effects of *APOE*  $\epsilon 4$  carriage in  $A\beta-$  CN adults [18,19]. While a series of well-designed and large prospective studies have shown that *APOE*  $\epsilon 4$  carriage is associated with increased decline in episodic memory and executive function [31–33], none of these have measured  $A\beta$  levels in their sample. Given that  $\epsilon 4$  carriage increases the risk of  $A\beta+$  it is likely in these studies that the effect of *APOE*  $\epsilon 4$  on cognitive decline is mainly due to the interaction between  $A\beta$  and  $\epsilon 4$  rather than an effect of  $\epsilon 4$  by itself [34,35]. Caselli and colleagues have emphasised that within groups of cognitively normal  $\epsilon 4$  carriers, those who are homozygous for the  $\epsilon 4$  allele show much greater decline than heterozygotes [31]. This raises a challenge for interpreting the current data, as well as for data from previous studies reporting interactions between  $A\beta$  and *APOE*  $\epsilon 4$ , as none of these studies stratified their *APOE*  $\epsilon 4$  groups according to zygosity. While it is possible that  $A\beta$  related cognitive decline would be greater in *APOE*  $\epsilon 4$  homozygotes compared to *APOE*  $\epsilon 4$  heterozygotes, a test of this hypothesis would require the recruitment of very large samples of  $A\beta+$  CN older adults and may therefore be better investigated using meta-analytic methods.

Studies in humans and transgenic mice have shown that *APOE* is involved in AD pathogenesis both directly, through increasing  $A\beta$  accumulation, reducing clearance of  $A\beta$ , or modifying  $A\beta$ -synaptic toxicity; and indirectly, through reducing synaptic plasticity, increasing neuroinflammation or affecting the concurrence of cerebrovascular events [10]. Similarly, one study has demonstrated that in humans,  $\epsilon 4$ , independent of  $A\beta$ , is associated with brain hypometabolism [36]. However, as the AIBL study excluded individuals with uncontrolled cardiovascular disease, the risk of concomitant cerebrovascular events over the 18-month interval is very low. Therefore it is possible that the faster memory decline observed in healthy  $A\beta+$   $\epsilon 4$  carriers was due to the direct effects of *APOE* on  $A\beta$  accumulation.

There is now much evidence from *in vitro*, animal, and human studies showing that isoforms of the apoE protein also affect risk for AD by differentially modulating  $A\beta$  clearance and accumulation in the brain; apoE4 increases  $A\beta$  accumulation and disrupts clearance relative to other apoE isoforms [11–14]. A recent *in vivo* study showed that the clearance of soluble  $A\beta$  in the brain interstitial fluid (ISF) depends on the isoform of human apoE expressed (apoE4 < apoE3  $\leq$  apoE2) [14]. This hypothesis accords with  $A\beta$  mouse models, which report that disruption of the apoE- $A\beta$  interaction can result in a significant reduction of  $A\beta$  plaques. Taken together, these data suggest that  $A\beta+$   $\epsilon 4$  related cognitive decline in preclinical AD may make an ideal target for drugs that moderate neurodegeneration arising from  $A\beta+$ , or from the interaction between  $A\beta+$  and  $\epsilon 4$  [10,21].

When considering the results of this study, as has been described previously, an important caveat is that the AIBL study is not a population-based sample [19, 29]. Cognitively normal older adults in the AIBL study were highly educated, and few had existing or untreated medical, neurological or psychiatric illnesses. Secondly, an extensive investigation of cognitive function was not conducted. The tasks used here were chosen based on their brevity, test-retest reliability, demonstrated sensitivity to short-term  $A\beta$ -related cognitive decline, and their use in current large secondary prevention clinical trials in preclinical AD. An exploration of more

detailed neuropsychological tests over the same short-term period will be useful in further elucidating the nature of  $A\beta$  and  $\epsilon 4$  related decline in cognitive function. Finally, as three radioligands were used to measure  $A\beta$ , SUVR data could not be integrated to form a single continuous measure of  $A\beta$  burden. However, there was no relationship between the proportion of individuals who were high and low  $A\beta+$  in  $A\beta+$   $\epsilon 4$  carriers and  $A\beta+$   $\epsilon 4$  non-carriers, suggesting that the faster decline observed in the  $A\beta+$   $\epsilon 4$  carriers was not due to more advanced disease at enrolment. However, these caveats notwithstanding, the results of the current study suggest that *APOE*  $\epsilon 4$  exacerbates the rate of  $A\beta$ -related memory decline in CN older adults, and support the consideration of *APOE*  $\epsilon 4$  status when interpreting cognitive endpoints of clinical trials in AD. Further, the current results support the growing number of studies reporting the synergistic effect of *APOE* and  $A\beta$  in affecting cognitive decline in preclinical AD. As the rate of cognitive decline in preclinical AD is significantly increased by the presence of *APOE*  $\epsilon 4$ , with some reports showing that  $A\beta+$   $\epsilon 4$  non-carriers do not show any decline in cognitive function even over 4-5 years, it is imperative that current secondary prevention clinical trials in preclinical AD consider the  $\epsilon 4$  status of individuals enrolled.

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## Author Contributions

Conceived and designed the experiments: CT YYL PM. Performed the experiments: CT YYL VLV SML. Analyzed the data: CT YYL PM. Contributed reagents/materials/analysis tools: DA RNM CLM PM VLV CCR KAE SRR SML. Wrote the paper: CT YYL PM.

## References

1. Corder E, Saunders A, Strittmatter W, Schmechel D, Gaskell P, Small GW, et al. (1993) Gene dose of apolipoprotein E type 4 allele and the risk of Alzheimer's disease in late onset families. *Science* 261: 921–923. PMID: [8346443](https://pubmed.ncbi.nlm.nih.gov/8346443/)
2. Small BJ, Rosnick CB, Fratiglioni L, Bäckman L (2004) Apolipoprotein E and cognitive performance: a meta-analysis. *Psychology and aging* 19: 592. PMID: [15584785](https://pubmed.ncbi.nlm.nih.gov/15584785/)
3. Villemagne VL, Pike KE, Chetelat G, Ellis KA, Mulligan RS, Bourgeat P, et al. (2011) Longitudinal assessment of  $A\beta$  and cognition in aging and Alzheimer disease. *Annals of neurology* 69: 181–192. doi: [10.1002/ana.22248](https://doi.org/10.1002/ana.22248) PMID: [21280088](https://pubmed.ncbi.nlm.nih.gov/21280088/)
4. Chetelat G, Villemagne VL, Bourgeat P, Pike KE, Jones G, Ames D, et al. (2010) Relationship between atrophy and  $\beta$ -amyloid deposition in Alzheimer disease. *Annals of neurology* 67: 317–324. doi: [10.1002/ana.21955](https://doi.org/10.1002/ana.21955) PMID: [20373343](https://pubmed.ncbi.nlm.nih.gov/20373343/)
5. Villemagne V, Pike K, Darby D, Maruff P, Savage G, Ng S, et al. (2008)  $A\beta$  deposits in older non-demented individuals with cognitive decline are indicative of preclinical Alzheimer's disease. *Neuropsychologia* 46: 1688–1697. doi: [10.1016/j.neuropsychologia.2008.02.008](https://doi.org/10.1016/j.neuropsychologia.2008.02.008) PMID: [18343463](https://pubmed.ncbi.nlm.nih.gov/18343463/)

6. Jack CR, Lowe VJ, Weigand SD, Wiste HJ, Senjem ML, Knopman DS, et al. (2009) Serial PIB and MRI in normal, mild cognitive impairment and Alzheimer's disease: implications for sequence of pathological events in Alzheimer's disease. *Brain*: awp062.
7. Chang S, ran Ma T, Miranda RD, Balestra ME, Mahley RW, Huang Y. (2005) Lipid- and receptor-binding regions of apolipoprotein E4 fragments act in concert to cause mitochondrial dysfunction and neurotoxicity. *Proceedings of the National Academy of Sciences of the United States of America* 102: 18694–18699. PMID: [16344479](#)
8. Valla J, Schneider L, Niedzielko T, Coon KD, Caselli R, Sabbagh MN, et al. (2006) Impaired platelet mitochondrial activity in Alzheimer's disease and mild cognitive impairment. *Mitochondrion* 6: 323–330. PMID: [17123871](#)
9. Valla J, Yaari R, Wolf AB, Kusne Y, Beach TG, Roher AE, et al. (2010) Reduced posterior cingulate mitochondrial activity in expired young adult carriers of the APOE  $\epsilon 4$  allele, the major late-onset Alzheimer's susceptibility gene. *Journal of Alzheimer's Disease* 22: 307–313. doi: [10.3233/JAD-2010-100129](#) PMID: [20847408](#)
10. Liu CC, Kanekiyo T, Xu H, Bu G (2013) Apolipoprotein E and Alzheimer disease: Risk, Mechanisms and Therapy. *Nature Reviews, Neurology* 9: 106–118. doi: [10.1038/nrneuro.2012.263](#) PMID: [23296339](#)
11. Jiang Q, Lee CY, Mandrekar S, Wilkinson B, Cramer P, Zelcer N, et al. (2008) ApoE promotes the proteolytic degradation of  $A\beta$ . *Neuron* 58: 681–693. doi: [10.1016/j.neuron.2008.04.010](#) PMID: [18549781](#)
12. Ji ZS, Miranda RD, Newhouse YM, Weisgraber KH, Huang Y, Mahley RW, et al. (2002) Apolipoprotein E4 potentiates amyloid beta peptide-induced lysosomal leakage and apoptosis in neuronal cells. *Journal of Biological Chemistry* 277: 21821–21828. PMID: [11912196](#)
13. Ji ZS, Müllendorff K, Cheng IH, Miranda RD, Huang Y, Mahley RW. (2006) Reactivity of apolipoprotein E4 and amyloid beta peptide: lysosomal stability and neurodegeneration. *Journal of Biological Chemistry* 281: 2683–2692. PMID: [16298992](#)
14. Belinson H, Kariv-Inbal Z, Kaye R, Masliah E, Michaelson DM (2010) Following activation of the amyloid cascade, apolipoprotein E4 drives the in vivo oligomerization of amyloid- $\beta$  resulting in neurodegeneration. *Journal of Alzheimer's Disease* 22: 959–970. doi: [10.3233/JAD-2010-101008](#) PMID: [20858958](#)
15. Lim YY, Ellis KA, Pietrzak RH, Ames D, Darby D, Harrington K, et al. (2012) Stronger effect of amyloid load than APOE genotype on cognitive decline in healthy older adults. *Neurology* 79: 1645–1652. doi: [10.1212/WNL.0b013e31826e9ae6](#) PMID: [23071163](#)
16. Doraiswamy PM, Sperling RA, Coleman RE, Johnson KA, Reiman EM, Davis MD, et al. (2012) Amyloid- $\beta$  assessed by florbetapir F 18 PET and 18-month cognitive decline. *Neurology* 79: 1636–1644. doi: [10.1212/WNL.0b013e3182661f74](#) PMID: [22786606](#)
17. Landau SM, Mintun MA, Joshi AD, Koeppe RA, Petersen RC, Aisen PS, et al. (2012) Amyloid deposition, hypometabolism, and longitudinal cognitive decline. *Annals of Neurology* 72: 578–586. doi: [10.1002/ana.23650](#) PMID: [23109153](#)
18. Mormino EC, Betensky RA, Hedden T, Schultz AP, Ward A, Huijbers W, et al. (2014) Amyloid and APOE E4 interact to influence short-term decline in preclinical Alzheimer's disease. *Neurology* 82: 1760–1767. doi: [10.1212/WNL.0000000000000431](#) PMID: [24748674](#)
19. Lim YY, Villemagne VL, Laws SM, Pietrzak RH, Snyder PJ, Ames D, et al. (2014) APOE and BDNF polymorphisms moderate amyloid  $\beta$ -related cognitive decline in preclinical Alzheimer's disease. *Molecular Psychiatry* epub. doi: [10.1038/mp.2014.123](#) PMID: [25288138](#)
20. Lim YY, Villemagne VL, Pietrzak RH, Ames D, Ellis KA, Harrington K, et al. (2015) APOE  $\epsilon 4$  moderates amyloid-related memory decline in preclinical Alzheimer's disease. *Neurobiology of Aging* 36: 1239–1244. doi: [10.1016/j.neurobiolaging.2014.12.008](#) PMID: [25559335](#)
21. Kanekiyo T, Xu H, Bu G (2014) ApoE and  $A\beta$  in Alzheimer's disease: Accidental encounters or partners? *Neuron* 81: 740–754. doi: [10.1016/j.neuron.2014.01.045](#) PMID: [24559670](#)
22. Caselli RJ, Locke DEC, Dueck AC, Knopman DS, Woodruff BK, Hoffman-Snyder C, et al. (2014) The neuropsychology of normal aging and preclinical Alzheimer's disease. *Alzheimer's & Dementia* 10: 84–92. doi: [10.1016/j.jalz.2013.01.004](#) PMID: [23541188](#)
23. Salloway S, Sperling R, Fox NC, Blennow K, Klunk W, Raskind M, et al. (2014) Two phase 3 trials of bapineuzumab in mild-to-moderate Alzheimer's disease. *The New England Journal of Medicine* 370: 322–333. doi: [10.1056/NEJMoa1304839](#) PMID: [24450891](#)
24. Doody RS, Thomas RG, Farlow M, Iwatsubo T, Vellas B, Joffe S, et al. (2014) Phase 3 trials of solanezumab for mild-to-moderate Alzheimer's disease. *The New England Journal of Medicine* 370: 311–321. doi: [10.1056/NEJMoa1312889](#) PMID: [24450890](#)

25. Ellis KA, Bush AI, Darby D, De Fazio D, Foster J, Hudson P, et al. (2009) The Australian Imaging, Biomarkers and Lifestyle (AIBL) study of aging: methodology and baseline characteristics of 1112 individuals recruited for a longitudinal study of Alzheimer's disease. *International Psychogeriatrics* 21: 672–687. doi: [10.1017/S1041610209009405](https://doi.org/10.1017/S1041610209009405) PMID: [19470201](https://pubmed.ncbi.nlm.nih.gov/19470201/)
26. Rowe CC, Bourgeat P, Ellis KA, Brown B, Lim YY, Mulligan R, et al. (2013) Predicting Alzheimer disease with  $\beta$ -amyloid imaging: Results from the Australian imaging, biomarkers, and lifestyle study of ageing. *Annals of Neurology* 74: 905–913. doi: [10.1002/ana.24040](https://doi.org/10.1002/ana.24040) PMID: [24448836](https://pubmed.ncbi.nlm.nih.gov/24448836/)
27. Lim YY, Maruff P, Pietrzak RH, Ames D, Ellis KA, Harrington K, et al. (2014) Effect of amyloid on memory and non-memory decline from preclinical to clinical Alzheimer's disease. *Brain* 137: 221–231. doi: [10.1093/brain/awt286](https://doi.org/10.1093/brain/awt286) PMID: [24176981](https://pubmed.ncbi.nlm.nih.gov/24176981/)
28. Lim YY, Maruff P, Pietrzak RH, Ellis KA, Darby D, Ames D, et al. (2014) A $\beta$  amyloid and cognitive change: Examining the preclinical and prodromal stages of Alzheimer's disease. *Alzheimer's & Dementia* S1552–5260: 02939–02937. doi: [10.1016/j.jalz.2013.11.005](https://doi.org/10.1016/j.jalz.2013.11.005) PMID: [24589436](https://pubmed.ncbi.nlm.nih.gov/24589436/)
29. Villemagne VL, Burnham S, Bourgeat P, Brown B, Ellis KA, Salvado O, et al. (2013) Amyloid  $\beta$  deposition, neurodegeneration, and cognitive decline in sporadic Alzheimer's disease: a prospective cohort study. *The Lancet Neurology* 12: 357–367. doi: [10.1016/S1474-4422\(13\)70044-9](https://doi.org/10.1016/S1474-4422(13)70044-9) PMID: [23477989](https://pubmed.ncbi.nlm.nih.gov/23477989/)
30. Jack CR Jr, Knopman DS, Jagust WJ, Shaw LM, Aisen PS, Weiner MW, et al. (2010) Hypothetical model of dynamic biomarkers of the Alzheimer's pathological cascade. *The Lancet Neurology* 9: 119–128. doi: [10.1016/S1474-4422\(09\)70299-6](https://doi.org/10.1016/S1474-4422(09)70299-6) PMID: [20083042](https://pubmed.ncbi.nlm.nih.gov/20083042/)
31. Caselli RJ, Dueck AC, Osborne D, Sabbagh MN, Connor DJ, Ahern GL, et al. (2009) Longitudinal modeling of age-related memory decline and the APOE  $\epsilon 4$  effect. *New England Journal of Medicine* 361: 255–263. doi: [10.1056/NEJMoa0809437](https://doi.org/10.1056/NEJMoa0809437) PMID: [19605830](https://pubmed.ncbi.nlm.nih.gov/19605830/)
32. Storandt M, Mintun MA, Head D, Morris JC (2009) Cognitive decline and brain volume loss as signatures of cerebral amyloid- $\beta$  peptide deposition identified with Pittsburgh compound B: cognitive decline associated with A $\beta$  deposition. *Archives of Neurology* 66: 1476–1481. doi: [10.1001/archneurol.2009.272](https://doi.org/10.1001/archneurol.2009.272) PMID: [20008651](https://pubmed.ncbi.nlm.nih.gov/20008651/)
33. Small BJ, Basun H, Bäckman L (1998) Three-year changes in cognitive performance as a function of apolipoprotein E genotype: evidence from very old adults without dementia. *Psychology and aging* 13: 80. PMID: [9533192](https://pubmed.ncbi.nlm.nih.gov/9533192/)
34. Schmechel D, Saunders A, Strittmatter W, Crain BJ, Hulette C, Joo SH, et al. (1993) Increased amyloid beta-peptide deposition in cerebral cortex as a consequence of apolipoprotein E genotype in late-onset Alzheimer disease. *Proceedings of the National Academy of Sciences* 90: 9649–9653.
35. Hashimoto T, Serrano-Pozo A, Hori Y, Adams KW, Takeda S, Banerji AO, et al. (2012) Apolipoprotein E, especially apolipoprotein E4, increases the oligomerization of amyloid  $\beta$  peptide. *The Journal of Neuroscience* 32: 15181–15192. doi: [10.1523/JNEUROSCI.1542-12.2012](https://doi.org/10.1523/JNEUROSCI.1542-12.2012) PMID: [23100439](https://pubmed.ncbi.nlm.nih.gov/23100439/)
36. Jagust WJ, Landau SM (2012) Apolipoprotein E, not fibrillar  $\beta$ -amyloid, reduces cerebral glucose metabolism in normal aging. *Journal of Neuroscience* 32: 18227–18233. doi: [10.1523/JNEUROSCI.3266-12.2012](https://doi.org/10.1523/JNEUROSCI.3266-12.2012) PMID: [23238736](https://pubmed.ncbi.nlm.nih.gov/23238736/)