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RESEARCH ARTICLE

Learning deficit in cognitively normal APOE ϵ 4 carriers with LOW β -amyloid

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Abstract

Introduction: In cognitively normal (CN) adults, increased rates of amyloid beta ($A\beta$) accumulation can be detected in low $A\beta$ ($A\beta^-$) apolipoprotein E (APOE) ϵ 4 carriers. We aimed to determine the effect of ϵ 4 on the ability to benefit from experience (ie, learn) in $A\beta^-$ CNs.

Methods: $A\beta^-$ CNs ($n = 333$) underwent episodic memory assessments every 18 months for 108 months. A subset ($n = 48$) completed the Online Repeatable Cognitive Assessment-Language Learning Test (ORCA-LLT) over 6 days.

Results: $A\beta^-$ ϵ 4 carriers showed significantly lower rates of improvement on episodic memory over 108 months compared to non-carriers ($d = 0.3$). Rates of learning on the ORCA-LLT were significantly slower in $A\beta^-$ ϵ 4 carriers compared to non-carriers ($d = 1.2$).

Discussion: In $A\beta^-$ CNs, ϵ 4 is associated with a reduced ability to benefit from experience. This manifested as reduced practice effects (small to moderate in magnitude) over 108 months on the episodic memory composite, and a learning deficit (large in magnitude) over 6 days on the ORCA-LLT. Alzheimer's disease (AD)-related cognitive abnormalities can manifest before preclinical AD thresholds.

KEYWORDS

Alzheimer's disease, amyloid, apolipoprotein E, learning, memory

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1 | INTRODUCTION

In cognitively normal (CN) older adults, elevated amyloid beta ($A\beta+$) is associated with episodic memory dysfunction, hippocampal volume loss, accumulation of $A\beta$, and increased rate of progression to mild cognitive impairment (MCI) or dementia, relative to matched adults with low $A\beta$ ($A\beta-$).^{1,2} The severity of these clinical and biological manifestations of $A\beta+$ is increased further by the apolipoprotein E (APOE) $\epsilon 4$ allele.^{3,4} Proposed to be a consequence of $\epsilon 4$ disrupting normal $A\beta$ clearance.⁵ Subtle but increased rates of $A\beta$ accumulation over 3 to 4 years can also be detected in $\epsilon 4$ carriers who remain $A\beta-$,⁶ raising the possibility that cognitive changes may be detectable in $A\beta-\epsilon 4$ carriers if the study design or cognitive assessments applied have sufficient sensitivity.

In the Australian Imaging, Biomarkers and Lifestyle (AIBL) study, CNs completed seven neuropsychological assessments over 108 months providing greater power than previous investigations of $A\beta-$ groups to understand the effects of $\epsilon 4$ on cognition.^{3,7} However, prospective investigations of cognitive change in AIBL, and in similar longitudinal cohorts, now show that in $A\beta+$ CNs, episodic memory remains stable over 5 to 6 years, whereas in matched $A\beta-$ CNs, memory improves substantially over the same interval (ie, a practice effect).⁸⁻¹¹ Reduced practice effects are proposed to be a strong clinical marker of early Alzheimer's disease (AD) pathologic changes in preclinical AD,^{9,11} and are therefore likely to occur in CN $A\beta-\epsilon 4$ carriers. However, we have argued that a more parsimonious conceptualization of observations of reduced practice effects is that in very early AD, deficits in the ability to benefit from experience (ie, to learn) are greater than deficits in memory retrieval; at least as when measured by standardized tests of episodic memory.^{10,12} We challenged this hypothesis in preclinical AD, and found that deficits on a formal learning paradigm, evident over 6 days, were four times greater than the abnormal change in episodic memory detected across the prior 6 years.¹² Application of this learning model may therefore also inform understanding of any AD-related cognitive dysfunction in CN $A\beta-\epsilon 4$ carriers.

2 | METHODS

2.1 | Participants

$A\beta-$ CN older adults ($n = 333$) enrolled in the AIBL study provided a blood sample for APOE genotyping, and underwent serial neuropsychological assessments every 18 months, for at least three timepoints. A subgroup of these participants ($n = 48$), naïve to Chinese, Japanese or Korean languages, also participated in a 6-day learning challenge (Figure 1 summarizes the number of participants contacted, eligible, enrolled, and included in this analysis). No participant had progressed to MCI/AD. Recruitment and inclusion/exclusion criteria of AIBL have been described previously.^{13,14} A clinical panel comprised of geriatricians, neurologists, and neuropsychologists determined the cognitive normality of participants by examining all available medical and

RESEARCH IN CONTEXT

Systematic Review: The authors reviewed the literature using traditional (eg, PubMed) sources, meeting abstracts, and presentations. Studies reporting on the role of apolipoprotein E (APOE) in low amyloid beta ($A\beta$)–cognitively normal older adults were included. Studies on practice effects in the context of aging and Alzheimer's disease (AD) were also reviewed.

Interpretation: Our findings are novel in showing that reduced ability to benefit from experience (ie, learn) is evident in $A\beta-\epsilon 4$ carriers. This manifested as reduced practice effects over 108 months on the episodic memory composite, albeit of a small-to-moderate magnitude, and a learning deficit that was large in magnitude over 6 days on the Online Repeatable Cognitive Assessment–Language Learning Test (ORCA-LLT).

Future Directions: Future studies are required to determine the extent to which other neuroinflammatory, cerebrovascular, or neurodegenerative processes may be related to this learning deficit in $A\beta-$ adults.

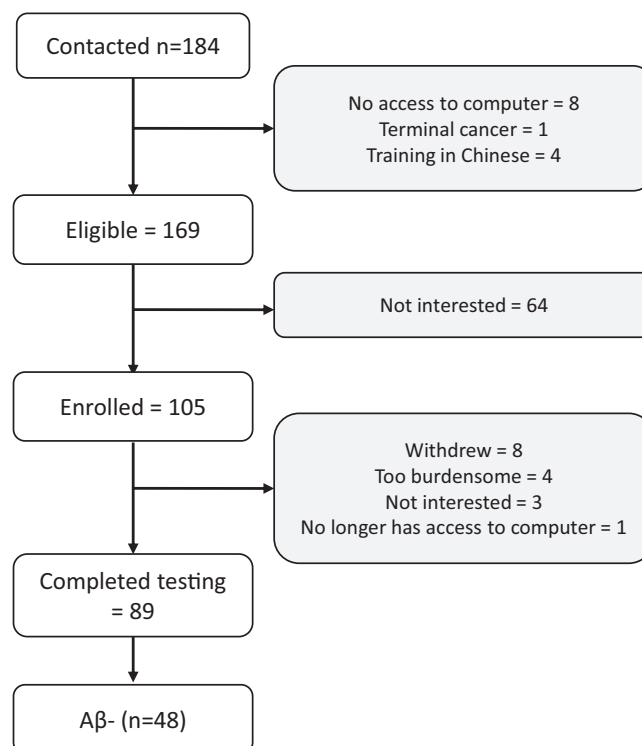


FIGURE 1 Flowchart of the number of participants contacted, enrolled, and completed Online Repeatable Cognitive Assessment–Language Learning Test (ORCA-LLT)

TABLE 1 Demographic, clinical, cardiovascular, and neuroimaging characteristics

	AIBL CN sample			ORCA CN subsample		
	A β - ϵ 4- (n = 273)	A β - ϵ 4+ (n = 60)	p	A β - ϵ 4- (n = 35)	A β - ϵ 4+ (n = 13)	p
	Mean (SD)	Mean (SD)		Mean (SD)	Mean (SD)	
N, Female (%)	154 (46.2)	33 (55.0)	.842	18 (60.0)	5 (41.7)	.281
Age at first assessment, y	69.37 (5.87)	67.69 (5.51)	.044	74.40 (4.93)	73.85 (5.24)	.735
Years of education	12.36 (2.96)	12.48 (3.05)	.790	13.85 (2.87)	12.15 (3.11)	.083
HADS-anxiety†	4.42 (2.85)	4.79 (3.58)	.472	3.65 (2.97)	4.00 (3.70)	.735
HADS-depression†	2.60 (2.25)	3.11 (2.44)	.211	2.32 (2.23)	3.08 (2.66)	.331
MMSE†	28.86 (1.20)	28.94 (1.10)	.616	29.12 (1.04)	29.15 (1.21)	.919
CDR Sum of Boxes†	0.03 (0.16)	0.04 (0.14)	.736	0.04 (0.19)	0.19 (0.43)	.108
Body mass index	26.87 (4.15)	26.25 (3.61)	.305	26.45 (3.67)	25.39 (3.17)	.433
Abdominal circumference, cm	92.98 (13.28)	92.44 (13.19)	.790	89.66 (11.27)	90.70 (7.62)	.795
Diastolic blood pressure, mmHg	79.15 (10.33)	77.24 (8.73)	.192	81.48 (9.18)	78.60 (7.72)	.394
Systolic blood pressure, mmHg	136.52 (15.34)	139.19 (15.22)	.230	136.74 (15.99)	136.80 (7.76)	.991
Centiloid†	1.71 (9.87)	2.70 (9.69)	.481	0.92 (4.63)	-0.60 (10.13)	.478
Hippocampal volume, cm ³ †	2.95 (0.29)	2.97 (0.25)	.686	2.94 (0.25)	3.01 (0.28)	.426
N years between first PET scan and baseline AIBL cognitive assessment	3.28 (2.54)	2.61 (2.39)	.064	–	–	–
N years between most recent PET scan and ORCA assessment	–	–	–	1.31 (1.22)	0.94 (0.84)	.319
N AIBL cognitive assessments	6.14 (1.20)	6.27 (1.12)	.464	5.21 (2.31)	4.69 (2.18)	.492

Abbreviations: AIBL, Australian Imaging, Biomarkers and Lifestyle Study; CDR, Clinical Dementia Rating; CN, cognitively normal; HADS, Hospital Anxiety and Depression Scale; MMSE, Mini-Mental State Examination; ORCA, Online Repeatable Cognitive Assessment; PET, positron emission tomography; SD, standard deviation.

† obtained from the PET scan for the AIBL CN sample and closest PET scan to ORCA-LLT assessment for the ORCA subsample; bolded values are significant at $P < .05$.

neuropsychological information. This clinical panel was blind to genetic and neuroimaging information. Participants were classified as cognitively normal if they performed greater than -1 standard deviation on all neuropsychological tests when compared to Australian norms, had a Mini-Mental State Examination (MMSE) score of 26 or greater, and a Clinical Dementia Rating (CDR) sum of boxes score of 0 or 0.5 (CDR sum of boxes score of 0.5 was acceptable if all neuropsychological tests were within normative ranges). Demographic characteristics are summarized in Table 1.

The AIBL study was approved by institutional research and ethics committees.¹⁴ Human research ethics approval to conduct this study was obtained through Melbourne Health.¹⁵ Informed consent was provided in writing prior to participation in this study.

2.2 | Episodic memory composite

The rationale and validation of the AIBL episodic memory composite has been described.³ Raw scores on the California Verbal Learning Test, Second Edition (CVLT-II) delayed recall trial, the Logical Memory delayed recall trial, and the Rey Complex Figure Test (RCFT)

30-minute delayed recall trial were standardized using the baseline mean and standard deviation of the A β - CN group, and averaged. As has been reported previously, identical forms of these memory tests were used at each assessment timepoint (administered in 18-month intervals).^{16,17}

2.3 | Learning test

The Online Repeatable Cognitive Assessment-Language Learning Test (ORCA-LLT) has also been described.^{12,15} This test measured the ability to learn the English language equivalent of 50 Chinese characters over six sessions. Participants were required to determine whether the English word and Chinese character had the same meaning. Sessions consisted of two blocks of 200 trials of both correct and incorrect pairs with each block requiring approximately 10 minutes to complete. Within each block, each Chinese character was presented four times in random order. For two of these presentations, the Chinese character was paired with the correct spoken English word. For the remaining two presentations, incorrect spoken English words were selected at random from the other possible 49 words. Each

day of the task provided unique sets of incorrect pairings, while the correct pairings stayed constant over time, to prevent off-target learning of incorrect pairs. Thus, the ratio of correct to incorrect pairings for the first day was 4:2, for the second day was 8:2, for the third day was 12:2, for the fourth day was 16:2, for the fifth day was 20:2, and for the final day was 24:2. The order of trials was randomized for each session and participant. Participants were unaware of the underlying ratio of correct to incorrect pairings, and no feedback regarding accuracy of the decision was provided to participants. The primary outcome of the ORCA-LLT was accuracy (percentage of correct responses).

2.4 | Neuroimaging

A β imaging with positron emission tomography (PET) was conducted using one of four radioligands: Pittsburgh Compound B, florbetapir, flutemetamol, or navidea. The acquisition protocol for each radioligand has been detailed previously.^{13,18} Threshold values for elevated A β deposition varied by radiotracer, so all standardized uptake value ratios (SUVR) were transformed onto the Centiloid scale using CapAIBL.^{19,20} A β - was classified if Centiloid scores were <15 at the closest imaging visit relative to participants' AIBL baseline cognitive assessment or ORCA assessment.

2.4.1 | Procedure

Participants completed the AIBL neuropsychological battery every 18 months. A subgroup completed the ORCA-LLT in their own homes through a web-based application using either a laptop or desktop computer daily for 6 days. Assessors of the AIBL neuropsychological battery and the ORCA-LLT were blind to A β neuroimaging and genetic results.

2.5 | Data analysis

Analyses were conducted using R v.3.5.0. Although data distributions for raw proportion correct performance scores on the ORCA-LLT were distributed normally (Shapiro-Wilks test, P s > .100 for all days), an arc-sine square-root transformation was applied prior to analyses. Arc-sine square-root transformations are used commonly for analyses of proportion correct scores as they increase the range of possible values when scales are bounded by chance (ie, 50%) and a perfect score (ie, 100%), which in turn can increase statistical power.²¹ To ensure that this normalization did not distort outcomes, we repeated analyses using raw proportion correct data to determine the similarity of conclusions drawn from analyses using transformed data.

Differences between APOE ϵ 4 carriers and non-carriers in the rate of change on the episodic memory composite were determined using a linear mixed-effects model (unstructured covariance matrix, maximum likelihood estimation, participant as random factor). Similarly, the difference between ϵ 4 carriers and non-carriers on the rate of learning on

the ORCA-LLT was determined using a linear mixed-effects model. For the ORCA-LLT, the Akaike information criterion (AIC) for the linear and quadratic models were 1534.18 and 1554.17, respectively, with the linear model demonstrating a significantly better fit (lower AIC values), $\chi^2 = 52.99$, $P < .001$. Similarly, for the episodic memory composite, the AIC for the linear and quadratic models were 4023.22 and 4042.91, with the quadratic model not significantly better than the linear model, $\chi^2 = 1.53$, $P = .465$. Age was included as a covariate in all models. The unit of time for both mixed-effects models was test session (ie, months for the episodic memory composite and days for ORCA-LLT). Cohen's d was used to express the magnitude of between-group differences.

3 | RESULTS

3.1 | Sample characteristics

APOE ϵ 4 carriers were slightly younger than ϵ 4 non-carriers, but were equivalent on other demographic, clinical, cardiovascular, and neuroimaging characteristics (Table 1). In the ORCA sub-sample, ϵ 4 carriers and non-carriers were matched on all demographic, clinical and neuroimaging characteristics. The average completion rate for the ORCA-LLT was 98% across all days, with the lowest completion rate observed on Day 6 (ie, 96%).

3.2 | Effect of APOE ϵ 4 on episodic memory and short-term learning

For the episodic memory composite, a significant ϵ 4 x time interaction was observed. Decomposition of the interaction indicated that A β - CN ϵ 4 carriers demonstrated a significantly slower rate of improvement over 108 months compared to A β - CN ϵ 4 non-carriers (Figure 2A). This difference was small to moderate in magnitude (Table 2). Analyses of the ORCA-LLT learning curves indicated that ϵ 4 carriers showed significantly slower rates of learning compared to ϵ 4 non-carriers (modeled data in Figure 2B; raw data in Figure 2C), with the difference large in magnitude (Table 2). Re-analyses of the ORCA-LLT learning curves using untransformed data also yielded a significant interaction between APOE ϵ 4 and time, albeit with a smaller effect size, d (95% confidence interval) = 1.18 (0.48, 1.84), $P < .001$.

4 | DISCUSSION

Our study shows that in A β - CN older adults, the APOE ϵ 4 allele is associated with a reduced ability to learn, or put more broadly, as a reduced ability to benefit from experience. One manifestation of this is a reduction in the practice effect expected from 9 years of retesting on neuropsychological tests that yield the AIBL episodic memory composite (Figure 2A). However, despite the considerable length of follow-up, number of reassessments using the same versions of the memory tests, and sample size, the magnitude of the reduced practice effect in

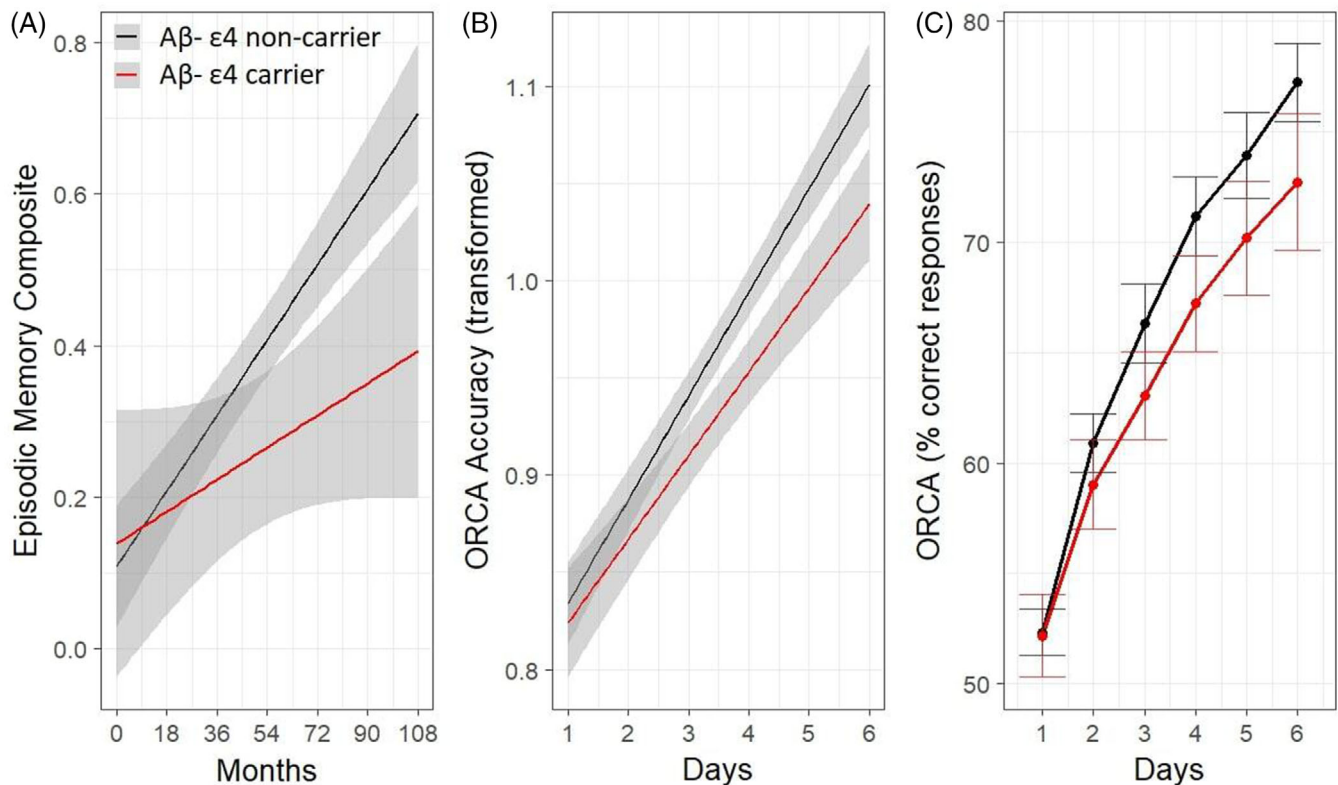


FIGURE 2 Effect of APOE $\epsilon 4$ on episodic memory performance over 108 months modeled using unadjusted estimates (A), and ORCA-LLT performance over 6 days, modeled using linear mixed model (B), and raw group means (C). Shaded areas and error bars represent 95% confidence intervals. A β , amyloid beta; APOE, apolipoprotein E; ORCA-LLT, Online Repeatable Cognitive Assessment-Language Learning Test

TABLE 2 Mean slopes (SD) and Cohen's d representing group mean slope differences from the mixed-effects model on episodic memory performance in the broader AIBL sample, and accuracy of performance on the ORCA-LLT

	AIBL CN full sample (outcome: EM composite)		ORCA CN subsample (outcome: ORCA-LLT accuracy)	
	β (SE)	P	β (SE)	P
APOE $\epsilon 4$	-0.195 (0.117)	.096	-0.311 (0.184)	.097
Age	-0.291 (0.045)	<.001	-0.028 (0.082)	.734
Time	0.148 (0.013)	<.001	0.752 (0.020)	<.001
APOE $\epsilon 4 \times$ Time	-0.068 (0.031)	.027	-0.147 (0.040)	<.001
	Mean (SD)	N	Mean (SD)	N
A β - $\epsilon 4$ non-carrier	0.148 (0.215)	273	0.752 (0.118)	35
A β - $\epsilon 4$ carrier	0.079 (0.215)	60	0.604 (0.126)	13
Cohen's d (95% CI)	0.32 (0.04, 0.60)		1.23 (0.53, 1.89)	

Abbreviations: AIBL, Australian Imaging, Biomarkers and Lifestyle (AIBL) study; APOE, apolipoprotein E; CI, confidence interval; CN, cognitively normal; EM, Episodic memory; ORCA-LLT, Online Repeatable Cognitive Assessment-Language Learning Test; SD, standard deviation; SE, standard error.

Notes: Bolded values are significant at $P < .05$; all β estimates reported have been standardized.

the A β -CN $\epsilon 4$ group was only small to moderate ($d = 0.3$). More proactively, in $\epsilon 4$ carriers, the reduced ability to benefit from experience was evident from only 6 days of testing on the ORCA-LLT. In the ORCA paradigm, the failure to benefit from experience manifested in the substantially lower ability of the A β -CN $\epsilon 4$ carriers to learn a set of 50 Chi-

nese character-English word pairs, with the magnitude of this reduction much larger ($d = 1.2$) than that observed for the episodic memory composite (Figure 2B).

Reduced practice effects on episodic memory tests have been observed previously in preclinical AD groups from AIBL and other

prospective studies,^{8–10} although the magnitude of these reductions ($d = 0.4$) have been only slightly larger than those observed between the current sample of $A\beta$ - $\epsilon 4$ carriers and non-carriers. Recent investigations into $A\beta$ - individuals have identified subsets with faster $A\beta$ accumulation,⁷ particularly in $\epsilon 4$ carriers,⁶ although no study has observed memory decline in either AD risk groups when individuals who progressed to MCI/AD were excluded.⁷ The large deficit in learning observed in $A\beta$ - $\epsilon 4$ carriers on the ORCA-LLT is qualitatively similar to that reported previously, albeit with a slightly reduced magnitude, in the comparison of older adults with preclinical AD to $A\beta$ - controls (ie, $d > 2$).¹² While this learning deficit likely reflects the deleterious effects of accumulating $A\beta$ on the neurons or synapses necessary for the acquisition of new information, the precise biological basis of this interaction requires further exploration.

The learning paradigm used in the ORCA-LLT was based on experimental psychological models;^{22,23} however, the modification to require aspects of language learning makes the outcomes of this study directly generalizable to the functional aspects of daily living of older adults at risk of developing AD.¹⁵ The large learning deficit observed in older adults who carried a strong genetic risk factor for AD, but for whom $A\beta$ levels had not reached current thresholds of abnormality, suggest that the earliest AD-related cognitive dysfunction in otherwise CN older adults will be evident when they are required to acquire new and complex information, such as learning aspects of a new language. Future studies will be required to determine the extent to which acquisition of other novel and complex information would be similarly impaired (eg, learning a new technical procedure).

There are several limitations to consider when interpreting the results of our study. First, only a small subset of $A\beta$ - $\epsilon 4$ carriers completed the ORCA-LLT as the number of $\epsilon 4$ carriers who remained $A\beta$ - after 12 to 13 years of follow-up in AIBL was substantially reduced. However, despite our small sample size, we observed a high rate of completion (98%) on the ORCA-LLT. Additionally, our previous observation that short-term learning deficits in preclinical AD were very large ($d > 2$),¹² which provided reassurance that even with this relatively small sample size, we would have sufficient power to observe a qualitatively similar deficit in $A\beta$ - $\epsilon 4$ carriers. When considered together with the reduced practice effect observed over years, the learning deficits observed over days provides an important foundation for challenges of this approach in larger samples of older, or even middle-aged, $A\beta$ - $\epsilon 4$ carriers, which may help to further clarify the nature and magnitude of this effect and elucidate its bases in models of AD pathogenesis. Second, individuals with substantial cardiovascular disease were excluded from enrollment into the AIBL study. As such, while it is unlikely that the learning deficit observed here in $A\beta$ - $\epsilon 4$ carriers could be attributed to cardiovascular disease, it will be important for future studies to determine the extent to which other neuroinflammatory, cerebrovascular, or neurodegenerative processes may be related to this learning deficit. Finally, while the ORCA-LLT was designed to be a prospective measure of learning, we did not examine the extent to which performance on the ORCA-LLT changes over longer periods of time (eg, 1–2 years). It will be important for future

studies to determine whether the nature and magnitude of learning rates change over time.

These limitations notwithstanding, the consistent observation that AD risk factors such as $A\beta$ accumulation and $APOE \epsilon 4$ are associated with substantial learning deficits, that can be detected over days, supports the hypothesis that cognitive dysfunction in early AD manifests as a failure to benefit from experience. Furthermore, the presence of this large learning deficit in $A\beta$ - CN $\epsilon 4$ carriers shows, perhaps for the first time, that AD-related clinical abnormalities can manifest strongly in CN individuals even before they reach thresholds that currently define preclinical AD.

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CONFLICTS OF INTEREST

YY Lim, J Baker, A Mills, L Bruns Jr, C Fowler, J Fripp, SR Rainey-Smith, D Ames, CL Masters, and P Maruff report no conflicts of interest related to the article.

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REFERENCES

1. Jack CRJ, Wiste HJ, Therneau TM, Weigand SD, Knopman DS, Mielke MM, et al. Associations of amyloid, tau, and neurodegeneration biomarker profiles with rates of memory decline among individuals without dementia. *J Am Med Assoc*. 2019;321:2316–2325.
2. Baker JE, Lim YY, Pietrzak RH, Hassenstab J, Snyder PJ, Masters CL, et al. Cognitive impairment and decline in cognitively normal older adults with high amyloid- β : a meta-analysis. *Alzheimer's & Dementia: diagnosis. Alzheimers Dement (Amst)*. 2016;6:108–121.
3. Lim YY, Kalinowski P, Pietrzak RH, Laws SM, Burnham S, Ames D, et al. Association of β -amyloid and apolipoprotein E $\epsilon 4$ with memory decline in preclinical Alzheimer disease. *JAMA Neurol*. 2018;75:488–494.

4. Mormino EC, Betensky RA, Hedden T, Schultz AP, Ward A, Huijbers W, et al. Amyloid and APOE E4 interact to influence short-term decline in preclinical Alzheimer's disease. *Neurology*. 2014;82:1760-1767.
5. Liu CC, Kanekiyo T, Xu H, Bu G. Apolipoprotein E and Alzheimer disease: risk, mechanisms and therapy. *Nat Rev Neurol*. 2013;9:106-118.
6. Lim YY, Mormino EC. the Alzheimer's Disease Neuroimaging Initiative. APOE genotype and early β -amyloid accumulation in older adults without dementia. *Neurology*. 2017;89:1028-1034.
7. Landau S, Horng A, Jagust WJ. Memory decline accompanies sub-threshold amyloid accumulation. *Neurology*. 2018;90:e1452-e60.
8. Hassenstab J, Ruvo D, Jasielec M, Xiong C, Grant E, Morris JC. Absence of practice effects in preclinical Alzheimer's disease. *Neuropsychology*. 2015;29:940-948.
9. Duff K, Hammers DB, Dalley BCA, Suhrie KR, Atkinson TJ, Rasmussen KM, et al. Short-term practice effects and amyloid deposition: providing information above and beyond baseline cognition. *J Prev Alzheimers Dis*. 2017;4:87-92.
10. Baker JE, Pietrzak RH, Laws SM, Ames D, Villemagne VL, Rowe CC, et al. Visual paired associate learning deficits associated with elevated beta-amyloid in cognitively normal older adults. *Neuropsychology*. 2019. epub.
11. Jutten RJ, Grandoit E, Foldi NS, Sikkes SAM, Jones RN, Choi SE, et al. Lower practice effects as a marker of cognitive performance and dementia risk: a literature review. *Alzheimer's & Dementia: diagnosis. Alzheimers Dement (Amst)*. 2020;12:e12055.
12. Lim YY, Baker JE, Bruns L Jr, Mills A, Fowler C, Fripp J, et al. Association of deficits in short-term learning and A β and hippocampal volume in cognitively normal adults. *Neurology*. 2020. epub.
13. Rowe CC, Bourgeat P, Ellis KA, Brown B, Lim YY, Mulligan R, et al. Predicting Alzheimer disease with β -amyloid imaging: results from the Australian imaging, biomarkers, and lifestyle study of ageing. *Ann Neurol*. 2013;74:905-913.
14. Ellis KA, Bush AI, Darby D, De Fazio D, Foster J, Hudson P, et al. 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. *Int Psychogeriatr*. 2009;21:672-687.
15. Baker JE, Bruns Jr L, Hassenstab J, Masters CL, Maruff P, Lim YY. Use of an experimental language acquisition paradigm for standardized neuropsychological assessment of learning: a pilot study in young and older adults. *J Clin Exp Neuropsychol*. 2020;42:55-65.
16. Ellis KA, Rowe CC, Villemagne VL, Martins RN, Masters CL, Salvado O, et al. Addressing population aging and Alzheimer's disease through the Australian Imaging Biomarkers and Lifestyle study: collaboration with the Alzheimer's Disease Neuroimaging Initiative. *Alzheimers Dement*. 2010;6:291-296.
17. Lim YY, Maruff P, Pietrzak RH, Ames D, Ellis KA, Harrington K, et al. Effect of amyloid on memory and non-memory decline from preclinical to clinical Alzheimer's disease. *Brain*. 2014;137:221-231.
18. Villemagne VL, Pike KE, Ch  telat G, Ellis KA, Mulligan RS, Bourgeat P, et al. Longitudinal assessment of A β and cognition in aging and Alzheimer disease. *Ann Neurol*. 2011;69:181-192.
19. Bourgeat P, Dore V, Fripp J, Ames D, Masters CL, Salvado O, et al. Implementing the centiloid transformation for 11 C-PiB and β -amyloid 18 F-PET tracers using CapAIBL. *Neuroimage*. 2018;183:387-393.
20. Klunk WE, Koeppe RA, Price JC, Benzinger TL, Devous MDS, Jagust WJ, et al. The Centiloid Project: standardizing quantitative amyloid plaque estimation by PET. *Alzheimers Dement*. 2015;11:1-15.
21. Tabachnick BG, Fidell LS. *Using multivariate statistics (5th ed.)*. Needham Heights: Allyn & Bacon; 2006.
22. Breitenstein C, Knecht S. Development and validation of a language learning model for behavioral and functional-imaging studies. *J Neurosci Methods*. 2002;114:173-179.
23. Breitenstein C, Jansen A, Deppe M, Foerster AF, Sommer J, Wolbers T, et al. Hippocampus activity differentiates good from poor learners of a novel lexicon. *Neuroimage*. 2005;25:958-968.

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