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Semantic network function captured by word frequency in nondemented APOE ϵ 4 carriers

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Abstract

OBJECTIVE: Accurate identification of the earliest cognitive changes associated with Alzheimer's disease (AD) is critically needed. Item-level information within tests of category fluency, such as lexical frequency, harbors valuable information about the integrity of semantic networks affected early in AD. To determine the potential of lexical frequency as a cognitive marker of AD risk, we investigated whether lexical frequency of animal fluency output differentiated *APOE* ϵ 4 carriers from non-carriers in a cross-sectional design among older African American adults without dementia.

METHOD: We analyzed animal fluency performance using mean number of items and mean lexical frequency among 230 cognitively normal African Americans with and without the *APOE* ϵ 4 allele.

RESULTS: Lexical frequency was higher in *APOE* ϵ 4 carriers than non-carriers when analyzed as a mean score and within time bins. In contrast, we found no group difference in the number of items produced. Lexical frequency was particularly sensitive to ϵ 4-status after the first 10 seconds of the 60-second animal fluency task.

CONCLUSION: Our results suggest that psycholinguistic features may hold value as a cognitive biomarker for identifying people at high risk of AD.

Keywords

verbal fluency; category fluency; Alzheimer's disease; lexical frequency; psycholinguistic

1 Introduction

Deficits in semantic memory—general knowledge of facts, concepts, and the meaning of words—are well-known to be among the first clinical signs of Alzheimer’s disease (AD) (Butters, Granholm, Salmon, Grant, & Wolfe, 1987; Dudas, Clague, Thompson, Graham, & Hodges, 2005; Joubert et al., 2010; Petersen, Smith, Ivnik, Kokmen, & Tangalos, 1994). AD affects access to the underlying concept of a word (i.e., its meaning) (Joubert et al., 2010), and thus an often-reported symptom is subjective experience of word-finding difficulties (Clarnette, Almeida, Forstl, Paton, & Martins, 2001). Accurate identification of such early cognitive changes associated with AD is critically needed to support early detection. A convincing body of evidence from longitudinal studies has shown that cognitive change within an individual occurs years, even decades before clinical threshold for dementia occurs (Amieva et al., 2008; Bäckman, Jones, Berger, Laukka, & Small, 2005; Chen et al., 2001; Elias et al., 2000; Rajan, Wilson, Weuve, Barnes, & Evans, 2015). However, these changes are subtle and only detectable within-person over time (Papp et al., 2016). For example, the tests commonly used to assess verbal fluency, widely accepted as measures of semantic memory, usually focus on total correct score and the relative score of category fluency to letter fluency. These scores are sensitive markers for MCI (Murphy, Rich, & Troyer, 2006), AD (Monsch et al., 1992), and longitudinal decline in the preclinical stage of AD (Papp, Rentz, Orlovsky, Sperling, & Mormino, 2017), but are unable to detect preclinical AD on a cross-sectional basis (Papp et al., 2016).

Embedded in verbal fluency tasks, however, is qualitative, psycholinguistic information such as lexical frequency (i.e., how often a word occurs in daily language). Lexical frequency affects both word comprehension and production in healthy individuals, such that words with a higher frequency are recognized and produced more accurately and quicker than words with a lower frequency (Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2004; Kucera & Francis, 1982). Moreover, lexical frequency influences language decline in neurological conditions, including AD (Balota, Burgess, Cortese, & Adams, 2002; Bird, Lambon Ralph, Patterson, & Hodges, 2000; Kremin et al., 2001). Semantic decline in AD first affects words with low frequency (Bird et al., 2000). For example, patients with progressive semantic impairment are likely to lose lower frequency words first (e.g., lynx, platypus, puma) before more frequent words become affected (e.g., dog, horse, bird). Thus, analyses of the item-level lexical frequency of fluency output may reveal reduced depth and extent of the integrity of the semantic network and may be able to detect AD-related cognitive decline at an earlier stage than the traditional “total correct” score.

The current study is part of a larger project investigating the genetic and environmental pathways of AD pathogenesis in African Americans (Hamilton et al., 2014; Meier et al., 2012). The epsilon 4 allele of the apolipoprotein E gene (*APOE* ϵ 4) is a well-established risk factor for AD (Corder et al., 1993; Evans et al., 1997; Honig, Schupf, Lee, Tang, & Mayeux, 2006; Tang et al., 1998). While the relative risk for AD associated with *APOE* ϵ 4 is lower among African Americans than among non-Hispanic Whites (Tang et al., 1996), several studies have shown that African Americans who are homo- or heterozygous for the ϵ 4 allele are at increased odds of developing AD and cognitive impairment (Farrer et al., 1997; Graff-Radford et al., 2002; Hendrie et al., 1995; Logue et al., 2011; Reitz et al., 2013;

Sinha et al., 2018). Multiple studies show that among cognitively healthy older adults, and independent of demographic variables such as age, sex, and education, African Americans obtain lower neuropsychological scores compared with non-Hispanic Whites, including measures of category fluency (Gladsjo et al., 1999; Johnson-Selfridge, Zalewski, & Abouadarham, 1998; Manly et al., 1998; Manly, Jacobs, Touradji, Small, & Stern, 2002). The current study sought to identify whether a novel measure of cognitive functioning could detect differences between individuals at higher genetic risk for AD compared with those at lower risk in this less well-studied population.

To determine the potential of lexical frequency as a cognitive marker of AD risk, we investigated whether lexical frequency of animal fluency output differentiated *APOE* $\epsilon 4$ carriers from non-carriers in a cross-sectional design among older African American adults without dementia. Given that AD is thought to first affect low-frequency words, we hypothesized that mean lexical frequency would predict AD genetic risk (having the *APOE* $\epsilon 4$ allele). In contrast, we hypothesized that the number of items generated during the animal fluency trial would not differ across *APOE* $\epsilon 4$ status. The total number of items per participant is variable, which intrinsically influences the mean lexical frequency value; therefore, we also performed time-bin analyses. We expected that when the items generated during the 60-second task were separated into 10-second bins, mean lexical frequency would lower across time, since most people start with familiar animals and produce less familiar exemplars as the task develops. Additionally, we expected between-group comparisons at each of the six time bins to show higher lexical frequency in the *APOE* $\epsilon 4$ carriers than non-carriers, but no difference in number of items.

2 Method

2.1. Participants

Participants were recruited from the African American Alzheimer's Disease Genetics Study, a multi-site effort including research teams from Columbia University, North Carolina A&T State University, University of Miami, and Vanderbilt University (recruitment and selection procedures described in detail in Hamilton et al. (Hamilton et al., 2014)). This study focused on the participants recruited at the Columbia University site, because their verbal fluency task performance was recorded and entered at the item-level across 10-second time bins.

A total of 230 cognitively healthy individuals (Clinical Dementia Rating, i.e., CDR = 0) were included, whose demographic characteristics are represented in Table 1. Inclusion criteria were for participants to have English as their first language, to be born in the United States, to self-identify as Black or African American and non-Hispanic based on U.S. Census criteria (Census Bureau, 2001), to be genetically tested for the *APOE* $\epsilon 4$ allele, and to have no history of reported clinical stroke, Parkinson's disease, Huntington's disease, or other non-AD dementia. The diagnosis of being cognitively healthy was made in a consensus case conference based on neurological, neuropsychological, medical, psychiatric, and functional evaluations following standard research criteria for MCI, all-cause dementia, AD, and other non-AD dementias (Albert et al., 2011; McKhann et al., 2011). The fluency measures were among multiple measures in the neuropsychological battery. Participants

gave written consent and were compensated for their participation in accordance with the Institutional Review Board at Columbia University Medical Center.

2.2. Materials and procedure

Participants were evaluated with a neuropsychological battery including tests of memory, orientation, language, abstract reasoning, and visuospatial ability, described in detail elsewhere (Hamilton et al., 2014; Meier et al., 2012). As part of their neuropsychological assessment, participants performed the animal fluency task. They were asked to verbally generate as many different animals as possible within 60 seconds. Their answers were written down within six 10-second blocks.

The analyses included correct items only. Each correctly produced word was paired with its log-transformed lexical frequency value from the SUBTLEXus database, which reflects the natural logarithmic value of how often a word form occurs per one million words in this corpus (<https://www.ugent.be/pp/experimentele-psychologie/en/research/documents/subtlexus>). The SUBTLEXus database is based on American subtitles of films and television series, a corpus of 51 million words that is validated to estimate American English daily language use closely (Brysbaert & New, 2009). A very small subset of words (0.69%) generated by participants included open form compound words (two words that together form one meaning, e.g., post office), for which alterations had to be made to derive a single-word frequency value.¹

Participants were genotyped for *APOE* as described by Hixson and Vernier (1990) with slight modification and categorized as *APOE* ϵ 4 positive (*APOE* ϵ 4+; n = 85; 81 heterozygote) or negative (*APOE* ϵ 4-; n = 145) based on the presence of the ϵ 4 allele.

2.3 Statistical analysis

Distributional characteristics of demographic and performance variables were derived with descriptive statistics. Subsequently, we tested their relation to each other with Pearson correlation coefficients and a point-biserial correlation, and across diagnostic groups with independent-samples t-tests and a chi-square test. Chi-square tests were also used to examine if there was a different proportion of compound words that required alteration between the two groups.

Mean lexical frequency was calculated for each individual based on the lexical frequency values of their produced words across 60 seconds, as well as per 10-second time bin. The predictive relation between the two measures of fluency performance and *APOE* ϵ 4 status was examined with logistic regression models; no covariates were entered into the models given that there were no demographic differences between the groups.

¹Alterations were made with *ad hoc* rules in the following order. If an open form compound word could be replaced with only the modifier of the compound and maintain the same meaning, we adjusted it accordingly (e.g., koala bear). If lexical frequency was available for a near-synonym, we imputed the value of the open form compound with that of the near-synonym (e.g., mountain lion to cougar). We imputed open form compounds with the lexical frequency of its modifier (i.e., the first word of the compound), postulating that that modifier in the majority of its occurrences is paired with that compound's head (i.e., the second word of the compound; e.g., polar for polar bear). If this assumption could not be made, we imputed the open form compound with the lexical frequency of its head (e.g., buffalo for water buffalo). No lexical frequency value was available in the database for the small mammal "pika" (n = 1), which was therefore imputed with a log value equal to an occurrence of one in a million.

Responses to the animal fluency task were recorded within one of six 10-second bins in which they were generated by the participant, which allowed us to investigate performance throughout the task. Because of the self-paced and continuous nature of the task, analyses of different time points throughout the task require a cumulative outcome of the performance up to each time bin. To characterize within- and between-group task performance over time, we performed growth curve models. Model-fit comparisons guided us to use a model with a random intercept and random slope fitting a quadratic polynomial growth curve.

In addition to trajectory across time bins, we performed comparisons of task performance between groups at each time bin. These time-binned analyses of mean lexical frequency per bin and mean number of items per bin used general linear models, in which separate models were performed for cumulative values up until the next time bin for each 10-second interval.

3. Results

3.1. Demographic characteristics

Individuals with and without *APOE* ε4 did not differ in age ($t(228) = .045, P = .965$), years of education ($t(228) = .153, P = .879$), sex ($\chi^2 = 0.047, P = .865$), MMSE score ($t(227) = .178, P = .859$) or WRAT-3 performance ($t(220) = -.236, P = .814$) (Table 1). There were also no differences in compound words that required alterations between the groups ($\chi^2 = 0.500, P = .479$). Animal fluency performance correlated with years of education (number of items: $r = .110, P = .097$; lexical frequency: $r = -.143, P = .030$) and WRAT-3 (number of items: $r = .227, P = .001$; lexical frequency: $r = -.274, P < .001$). Older participants generated fewer items ($r = -.329, P < .001$), while overall mean lexical frequency did not correlate with age ($r = .026, P = .695$).

3.2. Lexical frequency vs. number of items

Individuals with higher overall mean lexical frequency values had a higher probability to be *APOE* ε4+ than those with lower values ($P = .043$, odds ratio, OR = 4.853; 95% confidence interval, CI = 1.049–22.263). In contrast, the mean number of items was not predictive of *APOE* ε4 status ($P = .272$, OR = .962; 95% CI = .898–1.031).

Growth curve models to characterize within-group task performance over time (i.e., across the 10-second response bins within the same testing session) indicated that cumulative mean lexical frequency declined across time bins and cumulative number of items increased for both *APOE* ε4- and *APOE* ε4+ individuals (Table 2). Notably, pairwise comparisons between successive time bins showed that within each group, while significant as an overall trajectory, lexical frequency declined from the first to the second time bin but remained stable within the subsequent time bins (Table 3). In contrast, the number of words generated increased between every time bin.

In a growth curve model that included a group-by-time bin interaction, we observed a main effect between groups with a higher lexical frequency in *APOE* ε4+ than *APOE* ε4- individuals ($F(1, 212.769) = 3.912, P = .049$), while there was no main effect of group for number of items ($F(1, 227.942) = .604, P = .438$). There was no difference in change over time of lexical frequency or number of words between the two groups (Table 2).

We also characterized task performance between groups at each time bin by analyzing the difference in cumulative mean lexical frequency and cumulative number of words between the two groups for each of the six 10-second time bins (Figure 1). Except for within the first 10 seconds of the animal fluency task, the cumulative mean lexical frequency was lower in the *APOE* ϵ 4- group than in the *APOE* ϵ 4+ group in all remaining five time bins (Table 3). In contrast, none of the group comparisons of number of animals generated per bin were significant.

Qualitative inspection of participants' earliest responses reveals a clear pattern of what are considered stereotypical animals in the western world (i.e., pets, zoo animals, characters in children's books). For example, cat, dog, and lion were the top three most popular words to start with, as 70% of the people in the *APOE* ϵ 4- group and 74% in the *APOE* ϵ 4+ group used at least one of these within their first three produced words. As the task progressed, variety in answers increased. The observation that the majority of participants start animal fluency with the most familiar animals independent of *APOE* ϵ 4 status is compatible with our finding that differences in lexical frequency between groups were observed only after the first 10 seconds of this 60-second task.

4. Discussion

This study demonstrated that differences in semantic processing can be detected between older African American adults with and without the *APOE* ϵ 4 allele. We found that mean lexical frequency—a psycholinguistic characteristic of words—is uniquely sensitive to higher genetic risk for AD. The main effect of group on lexical frequency was not driven by a deviation from the 'normal' trajectory by the *APOE* ϵ 4+ group, but the *APOE* ϵ 4+ group consistently used higher frequency words than the *APOE* ϵ 4- group. Secondly, while number of items steadily decreased within the 60-second task window, lexical frequency was relatively stable after the first 10 seconds. While several previous studies were able to detect cognitive change within-person over time in *APOE* ϵ 4 carriers, biomarker-defined preclinical AD, or retrospectively in those who progressed to AD (M. W. Bondi et al., 1995; Elias et al., 2000; Papp et al., 2016), our ability to detect a difference in cognitive function between *APOE* ϵ 4 carriers and non-carriers using a cross-sectional design is novel.

Verbal fluency taps multiple cognitive skills, and total number of produced items does not fully capture the information available from task performance (Troyer, Moscovitch, Winocur, Leach, & Freedman, 1998). Valuable information about semantic function is hidden at the item level. Our results showed that nearly all participants start animal fluency with the most familiar animals (e.g., cat, dog), as exemplified by no significant differences in mean lexical frequency between *APOE* ϵ 4 groups in the first 10 seconds of the task. The rate of change for lexical frequency and number of items decreased across time bins, and did not differ between groups. However, between-*APOE* ϵ 4-group comparisons at each time bin showed the strongest differences within the second, third, and fourth 10-second bins. These findings suggest that the *APOE* ϵ 4+ participants had reduced ability to access less frequent words in their lexicon, especially after the first 10 seconds of the fluency task.

Previous research showed the validity of using item-level data to detect qualitative differences in fluency performance, including semantic decline in MCI and AD, through analyses of clustering in subcategories and switching between those beyond the power of the total number of items (Eng, Vonk, Salzberger, & Yoo, in press; Price et al., 2012; Troyer et al., 1998). A down-side of using clustering and switching measures is that they have to be manually coded and thus are time consuming and prone to rater bias. The lexical frequency measure used in this research study was easier to derive, and can be used by anyone with access to item-entered fluency data.

The earliest stages of AD are characterized by biological changes in the brain such as an accumulation of abnormal amyloid-beta and tau proteins and cerebral atrophy (Sperling et al., 2011). Several researchers claim that measures of cognitive ability are insensitive to these earliest biological changes that occur well before dementia and MCI criteria are met (Snyder et al., 2014), and claim that neuropsychological measures are the “last biomarker” to become abnormal in the trajectory of AD (Jack et al., 2013). Our results, however, suggest when the descriptive richness of participant responses is quantified (Ashendorf, Swenson, & Libon, 2013; Milberg, Hebben, Kaplan, Grant, & Adams, 2009), neuropsychological measures can be sensitive to AD risk when overall cognition and function are within normal limits, among people without subjective cognitive complaints (Mark W Bondi et al., 2014). These findings show the additive value of a qualitative approach in evaluating individuals at risk of AD. Future studies should explore the predictive strength of other psycholinguistic characteristics, such as age of acquisition and orthographic/phonological neighborhood density. Our sample consisted of exclusively African American individuals; therefore, a next step would be to examine lexical frequency in a multiethnic, multilingual cohort. While *APOE* ϵ 4 is a risk factor of AD, not all carriers develop the disease, and the relation between *APOE* ϵ 4 and AD is weaker among African Americans than among Whites (Farrer et al., 1997); therefore, we might expect that race/ethnicity will moderate the relationship between *APOE* ϵ 4 status and measures of semantic processing. Thus, future studies should compare lexical frequency among those with and without positive biomarkers such as PET amyloid neuroimaging and retrospectively analyze lexical frequency among those who do and do not develop incident AD.

In sum, fluency tasks are well-established as valuable neuropsychological measures for AD diagnosis and for tracking severity of cognitive dysfunction along the preclinical MCI-AD continuum, however, the “total correct” score on fluency measures at a single time point has not been sensitive to AD risk during the preclinical stage (Papp et al., 2016). The premise for the current study is that decline in semantic memory and conceptual formation occurs years before the clinical diagnosis of AD can be established (Amieva et al., 2008). We found that psycholinguistic analyses of fluency data has the potential to increase utility of neuropsychological instruments in detection of AD risk within the preclinical stage, and thus may refine the definition of high-risk populations for clinical trials.

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Public Significance Statement:

Decline in cognition occurs years before the symptoms are distinct enough to establish a clinical diagnosis of Alzheimer's disease based on traditional neuropsychological test scores. We showed that an alternative, psycholinguistic score of the category fluency task could predict AD genetic risk (having the *APOE* ϵ 4 allele) in older adults whose overall cognition and function are within normal limits. These results suggest that psycholinguistic features may hold value as a cognitive biomarker for identifying people at high risk of AD.

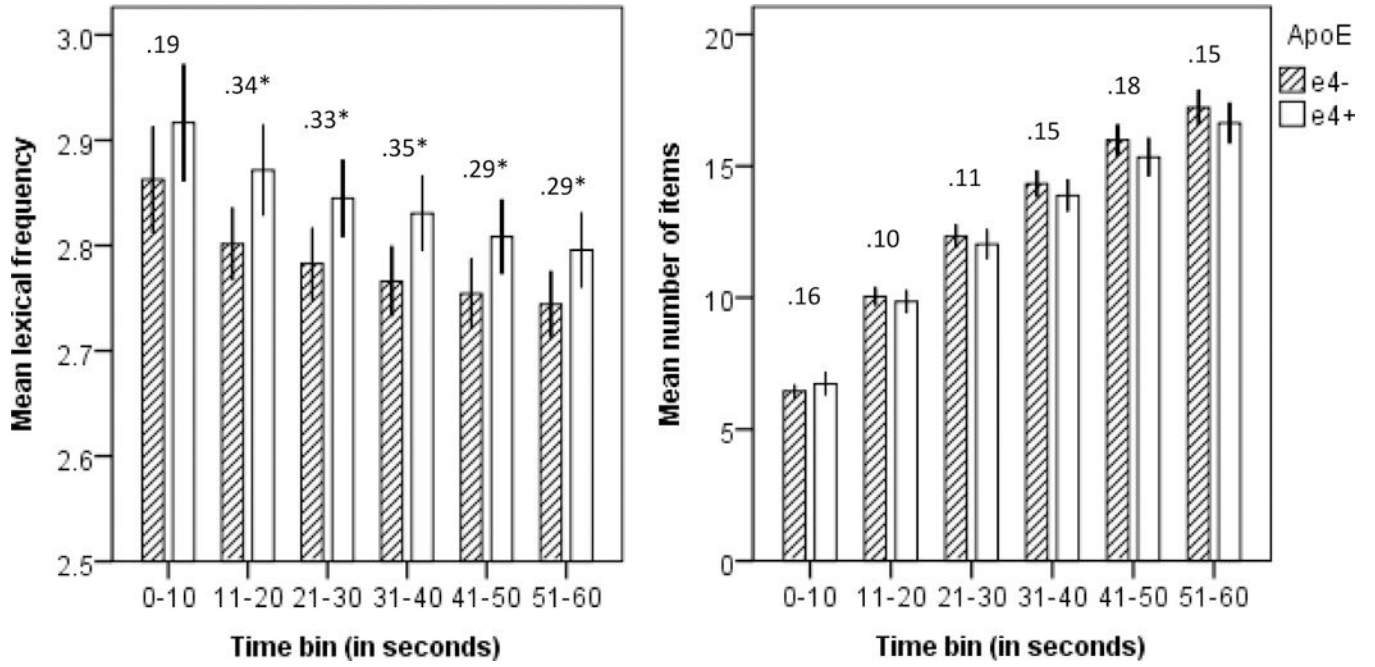


Figure 1. Animal fluency performance across task-time (number above bars represent effect size in Cohen's *d*; *significant at the .05 level; 95% confidence interval error bars)

Table 1.

Demographic information and animal fluency performance

	<i>APOE ε4-</i> (n = 145)	<i>APOE ε4+</i> (n = 85)
Demographics		
Age (years)	68.1 ±7.2 [55–86]	68.1 ±7.2 [55–86]
Sex	20% m, 80% f	19% m, 81% f
Years of education	14.6 ±2.8 [6–20]	14.6 ±2.4 [8–20]
MMSE	28.4 ±1.7 [21–30]	28.4 ±1.8 [20–30]
WRAT-3	45.5 ±6.0 [24–55]	45.6 ±4.9 [29–57]
Measures		
Mean lexical frequency	2.744 ±.194 [2.034–3.093]	2.796 ±.165 [2.431–3.221]*
Total number of items	17.2 ±4.1 [7–29]	16.6 ±3.6 [9–25]

NOTE. Values presented as mean ±standard deviation [range]; n, number of participants; m, male; f, female; MMSE = Mini-Mental State Examination; The Reading Recognition subtest from The Wide Range Achievement Test–Version 3 (WRAT-3) (Wilkinson, 1993) was used as a proxy for participants' quality of education (data missing for n = 8);

* $P < .05$

Table 2.

Growth curve parameters for standardized values of lexical frequency and number of items

	Lexical frequency				Number of items			
	<i>B</i>	<i>SE B</i>	<i>P</i>	95% CI	<i>B</i>	<i>SE B</i>	<i>P</i>	95% CI
<i>Total sample</i>								
Time bin (linear)	-0.242	0.033	< .001	-0.307; -0.178	0.806	0.02	< .001	0.766; 0.846
Time bin ² (quadratic)	0.02	0.004	< .001	0.012; 0.029	-0.052	0.002	< .001	-0.057; -0.047
APOE ε4 group	-0.292	0.147	0.049	-0.582; -0.001	-0.042	0.054	0.438	-0.148; 0.064
Time bin ² *group	0.002	0.003	0.531	-0.004; 0.009	0.002	0.003	0.511	-0.003; 0.007
<i>APOE ε4-</i>								
Time bin (linear)	-0.261	0.043	< .001	-.345; -.178	0.842	0.026	< .001	0.791; .892
Time bin ² (quadratic)	0.023	0.006	< .001	.012; .034	-0.055	0.003	< .001	-0.061; -.049
<i>APOE ε4+</i>								
Time bin (linear)	-0.21	0.051	< .001	-0.310; -.109	0.745	0.033	< .001	0.681; .809
Time bin ² (quadratic)	0.015	0.007	0.03	0.001; .028	-0.046	0.004	< .001	-.054; -.038

NOTE. *B* = estimate; *SE* = standard error; *P* = significance value; *CI* = confidence interval

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Table 3.

Comparisons between successive time bins within *APOE* ε4 groups and between *APOE* ε4 group comparisons per bin of lexical frequency and number of items

	<i>Lexical frequency</i>			<i>Number of items</i>		
	<i>APOE</i> ε4- Mean ±SD	<i>APOE</i> ε4+ Mean ±SD	Between group <i>P</i>	<i>APOE</i> ε4- Mean ±SD	<i>APOE</i> ε4+ Mean ±SD	Between group <i>P</i>
Bin 1	2.863 ±.308	2.917 ±0.259	0.176	6.4 ±1.6	6.7 ±1.9	0.236
	↕ <i>P</i> = < .001	↕ <i>P</i> = < .001		↕ <i>P</i> = < .001	↕ <i>P</i> = < .001	
Bin 2	2.801 ±.211	2.872 ±0.200	0.014	10.0 ±2.1	9.8 ±2.1	0.201
	↕ <i>P</i> = 0.163	↕ <i>P</i> = 0.102		↕ <i>P</i> = < .001	↕ <i>P</i> = < .001	
Bin 3	2.783 ±.208	2.845 ±0.171	0.021	12.3 ±2.8	12.0 ±2.6	0.296
	↕ <i>P</i> = 0.218	↕ <i>P</i> = 0.388		↕ <i>P</i> = < .001	↕ <i>P</i> = < .001	
Bin 4	2.766 ±.205	2.831 ±0.163	0.014	14.3 ±3.1	13.9 ±2.8	0.288
	↕ <i>P</i> = 0.378	↕ <i>P</i> = 0.172		↕ <i>P</i> = < .001	↕ <i>P</i> = < .001	
Bin 5	2.754 ±.203	2.808 ±0.166	0.038	16.0 ±3.7	15.3 ±3.4	0.195
	↕ <i>P</i> = 0.462	↕ <i>P</i> = 0.440		↕ <i>P</i> = < .001	↕ <i>P</i> = < .001	
Bin 6 [†]	2.744 ±.194	2.796 ±0.165	0.041	17.2 ±4.1	16.6 ±3.6	0.272

[†]NOTE. Equal to overall group comparison; SD = standard deviation; *P* = significance value;

↕ = pairwise comparison between time bins

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