Lexical and Sublexical Components of Age-related Changes in Neural Activation during Visual Word Identification

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Abstract

■ Positron emission tomography data (Madden, Langley, et al., 2002) were analyzed to investigate adult age differences in the relation between neural activation and the lexical (word frequency) and sublexical (word length) components of visual word identification. The differential influence of these components on reaction time (RT) for word/nonword discrimination (lexical decision) was generally similar for the two age groups, with word frequency accounting for a greater proportion of lexical decision RT variance relative to word length. The influence of word length on RT, however, was relatively greater for older adults. Activation in regions of the ventral occipito-temporal cortex was related to the RT changes associated with word frequency and length for older adults, but not for younger adults. Specifically, older adults' frequency effects were related to activation in both anterior (Brodmann's area [BA] 37) and posterior (BAs 17 and 18) regions of the occipito-temporal pathway, whereas word length effects were only associated with posterior activation (BA 17). We conclude that aging affects the neural mechanisms supporting word identification performance although behavioral measures of this ability are generally constant as a function of age. ■

INTRODUCTION

One of the most reliable findings in research on cognitive aging is that performance on tasks involving semantic memory (context-independent knowledge of word meanings and related concepts) is relatively constant as a function of increasing adult age, whereas episodic memory performance (involving context-dependent recollection of events) exhibits age-related decline (Burke, MacKay, & James, 2000; Wingfield & Stine-Morrow, 2000; Light, 1996). Neuroimaging investigations age-related changes in memory have focused primarily on episodic memory (Cabeza, 2001, 2002; Grady & Craik, 2000); relatively little is known about potential age-related changes in the neural systems mediating semantic memory performance. That is, although semantic memory performance is in many respects similar for younger and older adults, aging may lead to changes in the pattern of neural activation mediating this performance (Grossman et al., 2002; Madden, Langley, et al., 2002).

In this research, we compared younger and older adults' behavioral performance and neural activation in one type of semantic memory task, visual word identification. Behavioral studies have led to the view that different types of information about words are represented in separate subcomponents of semantic memory: an orthographic input lexicon that contains information about a word's visual features and shape and a semantic system that contains information about word meaning (Borowsky & Besner, 1993; Monsell, Doyle, & Haggard, 1989). When lexical decision (i.e., word/nonword discrimination) is used as a measure of word identification, it appears that information in both the orthographic and semantic systems is activated and used in response to task demands. When nonwords are pronounceable, for example, a correct response cannot be made entirely based on orthography, and the retrieval of some information related to word meaning is necessary.

A critical variable affecting reaction time (RT) and accuracy for lexical decision performance is the normative frequency of occurrence of words in printed text, with words of higher frequency being identified more quickly than lower frequency words. This word frequency effect appears to reflect lexical access processes (i.e., activation of the word's representation in memory) that are common to several types of word identification and categorization tasks, including lexical decision (Andrews & Heathcote, 2001; but cf. Balota & Chumbley, 1984). In addition, the effects of stimulus quality (e.g., intact vs. degraded items) on lexical decision performance tend to be statistically additive with those of word frequency, suggesting that the frequency effects

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occur beyond the level of the orthographic input lexicon and involve the semantic system to some extent (Borowsky & Besner, 1993). The effect of word frequency on lexical decision RT has frequently been observed to be similar for younger and older adults suggesting a preservation of lexical access, although responses are slower for the older adults overall (Allen, Madden, & Crozier, 1991; Allen, Madden, Weber, & Groth, 1993; Tainturier, Tremblay, & Lecours, 1989; but cf. Balota & Ferraro, 1996).

Word frequency is most often treated as a categorical variable (e.g., high- vs. low-frequency words), but additional information may be obtained by analyzing word frequency as a continuous variable. Spieler and Balota (2000) took this approach in their analysis of naming latencies for 2,820 words during a word-naming task. Consistent with previous investigations of word frequency categories, decreasing frequency (i.e., less familiarity) and increasing word length were associated with slower responding. In addition, the regression analyses demonstrated that frequency accounted for more variance in naming RT than did length for both age groups. Spieler and Balota found in addition that the relationship between frequency and RT was more pronounced (in terms of the magnitude of the regression coefficient) for older adults than for younger adults, whereas there was a nonsignificant trend for a greater relationship between word length and RT for younger adults relative to older adults. Spieler and Balota proposed that because age has a cumulative effect on reading experience, there is an increase in the influence of lexical factors (i.e., word-level variables such as familiarity) and a decrease in the influence of sublexical factors (i.e., those, like word length, related to the constituents of words), as a function of increasing adult age.

A number of neuroimaging investigations with younger adult participants have examined brain activation during various forms of word identification tasks, including reading words aloud (Herbster, Mintun, Nebes, & Becker, 1997; Price, Wise, Warburton, et al., 1996), reading silently (Price et al., 1994; Petersen, Fox, Snyder, & Raichle, 1990), lexical decision (Hart, Kraut, Kremen, Soher, & Gordon, 2000; Nenov, Halgren, Mandelkern, & Smith, 1994), and nonsemantic word processing (Price, Wise, & Frackowiak, 1996). Although visual word identification tasks lead to activation in many areas, especially in the left hemisphere, much of the research has focused on activations in the left inferior prefrontal and occipito-temporal regions (see Binder & Price, 2001; Kanwisher, Downing, Epstein, & Kourtzi, 2001, for reviews). The left prefrontal activations appear to include an anterior subregion (Brodmann's areas [BAs] 47 and 10) related to the processing of word meaning and a more posterior subregion (BAs 44 and 45) related to phonology (Fiez, 1997). Posterior occipito-temporal activations are thought to be particularly associated with processing at the orthographic (i.e., visual word form) level (e.g., Dehaene, Le Clec'H, Poline, Bihan, & Cohen, 2002; Polk & Farah, 2002), although more anterior regions of the occipito-temporal pathway, such as the inferior temporal gyrus, appear to contribute to analyses of word meaning (e.g., Chee, O'Craven, Bergida, Rosen, & Savoy, 1999; Binder et al., 1997).

Only a few studies (Madden, Langley, et al., 2002; Johnson et al., 2001; Madden et al., 1996) have addressed age-related changes in the neural systems mediating semantic memory. Both studies by Madden et al. measured regional cerebral blood flow (rCBF) via positron emission tomography (PET) during a lexical decision task. In the Madden et al. (1996) experiment, younger and older adults pressed a response button when a visually presented letter string was a word (e.g., bicycle) and withheld a response when the letter string was a pronounceable nonword (e.g., nardle). Madden et al. (1996) found that occipito-temporal activation during lexical decision, relative to a baseline task (responding to both words and nonwords), was higher for younger adults than for older adults. In a subsequent study using a nonsemantic baseline task (searching for a *c* among *T*s and *Z*s), Madden, Langley, et al. (2002) found that both age groups exhibited activation both in the left inferior prefrontal region and throughout the left occipito-temporal pathway (Figure 1). Activation was greater for older adults than for younger adults in more anterior areas of the occipito-temporal pathway (BA 37), whereas activation was relatively greater for younger adults in more posterior regions of this pathway (BA 17).

Previous findings from other cognitive tasks such as working memory (Rypma & D'Esposito, 2000) and visual search (Madden, Turkington, et al., 2002) suggest that the relation between neural activation and behavioral performance varies as a function of adult age. In the present analyses, we explored further the relation between lexical decision RT and rCBF activation in the Madden, Langley, et al. (2002) data. In the stimuli for this experiment, the sublexical variable of word length and the lexical variable of word frequency were relatively independent, in that the stimuli presented during each PET scan were selected so that the word targets represented a range of word frequency, but associated with each of several levels of word frequency there were also comparable ranges of word length. Madden, Langley, et al. (2002) reported correlations for mean RT and rCBF activation (in terms of PET radioactivity counts) but did not examine the potential influence of the frequency and length variables. In these analyses, we used the data from the individual items to obtain additional information regarding the sublexical and lexical components of age-related changes in word identification performance, as well as information regarding the relation of these components to rCBF activation.

Two issues were of particular interest. First, at the behavioral level, would the age-related increase in the influence of word frequency that Spieler and Balota (2000) observed in a word-naming task also be evident

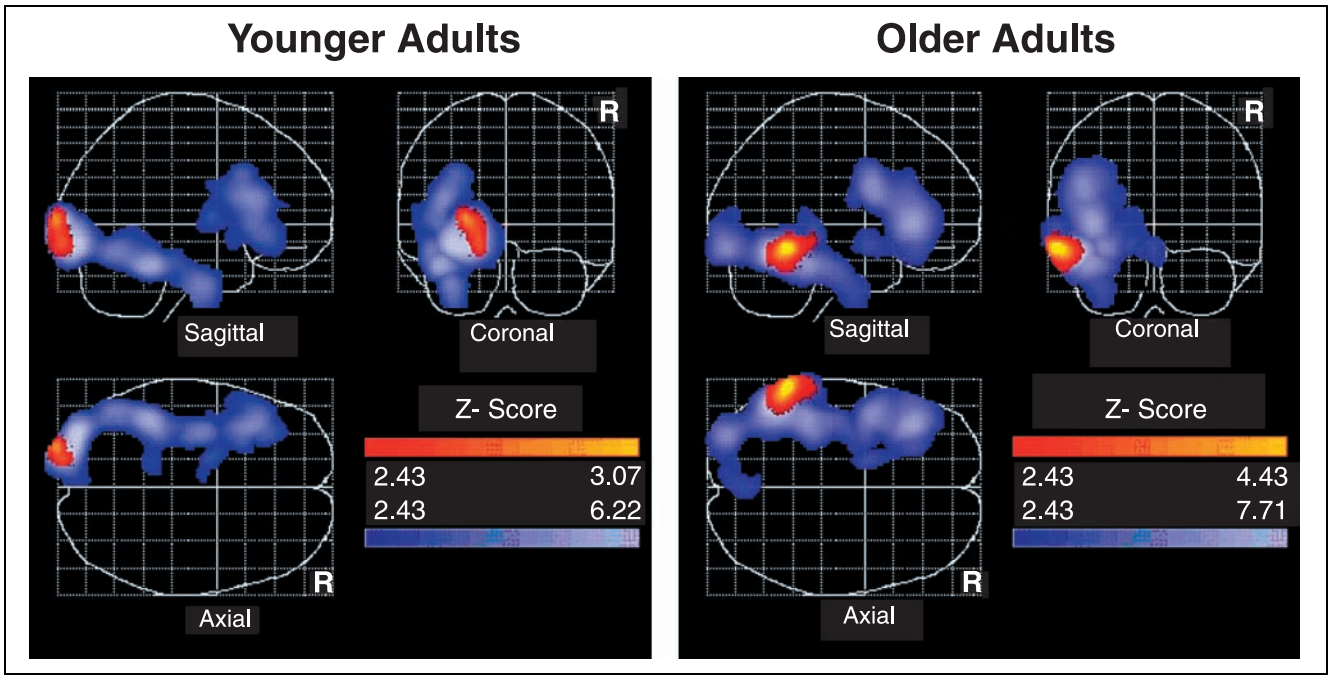

Figure 1. Areas of increased rCBF for a visual word identification task (lexical decision) relative to a simple visual search task (Madden, Langley, et al., 2002). The results are presented as SPM{*Z*} voxel maps in the sagittal, coronal, and axial planes, using the stereotaxic space of Talairach and Tournoux (1988). The images are presented in standard neurologic orientation, so that the right half of the coronal image and the lower half of the axial image correspond to the subject's right hemisphere. The rCBF increases for each age group are presented in the blue color scale values. Within each age group, those voxels that differed significantly from those of the other age group are presented in the red color scale values.

in a lexical decision task? Secondly, are the sublexical and lexical components of visual word identification related differentially to regional brain activation for younger and older adults? Spieler and Balota suggested that older adults' greater reliance on frequency during word naming was the result of the additional reading experience and familiarity with words gained with advancing age. If this assertion is true, then one might expect frequency effects to be associated with different patterns of activation between younger and older adults.

Our analysis consisted of three phases. As did Spieler and Balota (2000), we analyzed lexical decision RTs for the word targets by averaging RTs across participants to compute mean RTs for each of the word stimuli (720 words in all) used by Madden, Langley, et al. (2002). We then regressed word frequency and length onto RT for the younger and older adults' data separately. This procedure enabled us to determine, within each age group, the ability of word frequency and length to account for variance in lexical decision RT.[1] In the second phase, we analyzed data at the participant level using word frequency and length to predict RT for each participant. The standardized regression coefficients for frequency and length were then compared between age groups to determine whether the strength of relationship between the predictors and RT differed as a function of age. In the last phase of the analysis, we investigated the relation of word frequency and length to the PET counts for those two regions in the Madden et al. data for which the lexical decision−baseline subtraction yielded an age difference in the level of activation: left striate (BA 17) and left inferior temporal cortex (BA 37).

If lexical decision and word naming rely on similar lexical access processes, then regression analyses of our lexical decision data should confirm the pattern reported by Spieler and Balota (2000) for word naming, with word frequency having a larger influence on performance (in terms of accounting for variance in RT) than word length, and this pattern should be more prominent for older adults than for younger adults. Further, the age-related increase in left BA 37 activation, during word/nonword discrimination, reported by Madden, Langley, et al. (2002) may represent older adults' increased reliance on lexical (word-level) processing, in which case the relation between left BA 37 activation and the word frequency coefficients would be more pronounced for older adults than for younger adults. Conversely, the increased activation in left BA 17 for younger adults may be critical for word identification, but may represent sublexical processing that would be more closely related to word length than to word frequency.

RESULTS

Effects of Word Frequency and Length on Word Identification Reaction Time

To determine the proportion of variance in RT accounted for by word frequency and length, we submitted RTs for

Table 1. Multiple Regression Analysis of Frequency and Length on RT Using Simultaneous Entry of Predictors

Predictor	*Standardized Coefficient*	*t*	*p*	*Semipartial R^2*
*Younger adults**				
Frequency	−.497	12.71	.001	.168
Length	.101	2.59	.010	.007
*Older adults***				
Frequency	−.457	12.17	.001	.146
Length	.241	6.44	.001	.041

*R^2 = .255, $F(2,714) = 48.94$, $p < .001$.

**R^2 = .294, $F(2,714) = 59.60$, $p < .001$.

correct responses on word-target trials to regression analyses in which RT was the criterion variable, and word frequency (standard frequency index [SFI]) and length (number of letters) were continuous independent variables. As in the analyses by Spieler and Balota (2000), RTs for each of the 720 words were averaged across participants. Thus, each word had a value for frequency, length, and mean RT. Word frequency and length variables as well as lexical condition interaction terms were then entered simultaneously into the multiple regression equation to predict RT using separate regression equations for younger and older adults.[2]

The standardized regression coefficients, *t* values, and semipartialed R^2 (i.e., the variance in RT accounted for by a predictor when shared variance between that predictor and the other predictors in the equation has been partialed out) from the equations are presented in Table 1. The regression coefficients for frequency were negative, representing the increase in RT as word frequency decreases (i.e., as words become less familiar), whereas the coefficients for length were positive, representing the increase in RT as the number of letters in the word increases. Both frequency and length were reliable predictors of word-target RT for both younger and older adults, and for both age groups, frequency had a greater influence on RT than did length.

Given the significant influence that the predictor variables (frequency and length) had on RT within each age group, our next question focused on whether this influence varied as a function of either age group or predictor. Thus, standardized regression coefficients were obtained at the participant level by computing regression equations for each participant within each lexical condition, with RT as the criterion variable and frequency and length as simultaneous predictors. The mean values for these coefficients are presented in Figure 2. We then conducted an ANOVA on these coefficients with age group as a between-subjects variable and predictor (length, frequency) and lexical condition (lexical A, B, and C) as within-subjects variables. An alpha level of .05 was used to test all main effects and interactions.

The results indicated a main effect of predictor, $F(1,22) = 265.5$, $p < .01$, reflecting that coefficients for length were generally positive while those for frequency were negative. The effect of age approached significance, $F(1,22) = 4.13$, $p = .054$, which was likely driven by older adults' higher coefficients for length (see Figure 2B). The interactions of Age Group × Predictor, $F(1,22) = 5.11$, $p < .05$, and Age Group × Predictor × Condition, $F(2,44) = 3.64$, $p < .05$, were also significant.

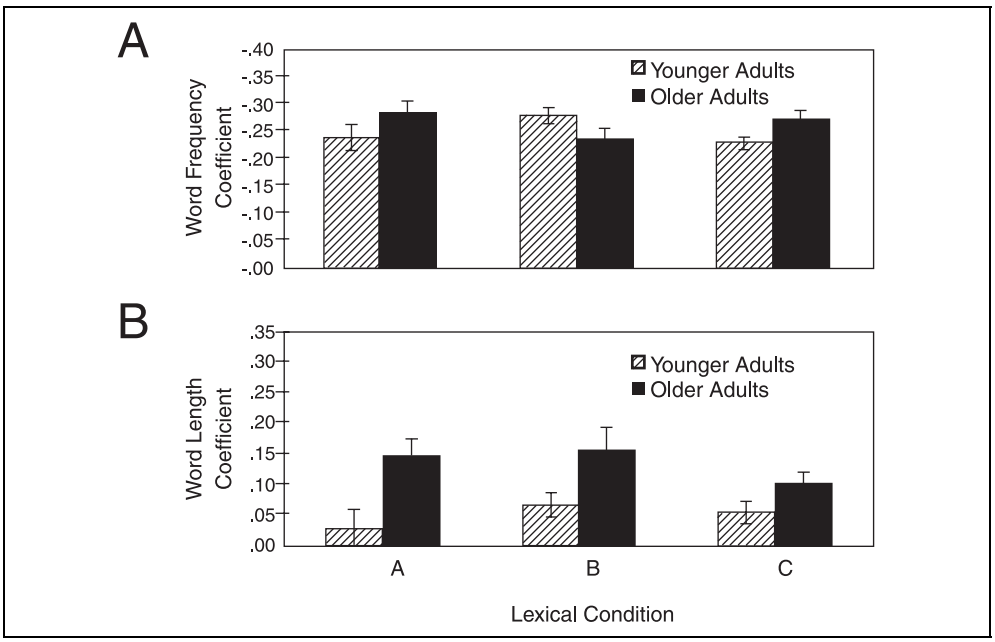

Figure 2. Mean (with standard error bars) word frequency (A) and length (B) regression coefficients as a function of age and lexical condition.

The two-way interaction occurred because the regression coefficients for frequency were equivalent for younger, and older adults (see Figure 2A), whereas the coefficients for length were greater for older adults than for younger adults, $t(70) = 3.78, p < .01$ (see Figure 2B). The three-way interaction represents relatively subtle changes in this pattern. When we analyzed frequency and length coefficients separately, the Age × Condition interaction was significant only for the frequency coefficients. The younger adults exhibited a slightly elevated frequency regression coefficient in the lexical A condition, but older adults' frequency coefficients did not vary by condition. The age difference in the word frequency coefficients was not significant within any of the lexical conditions.

Relationship of Regional Cerebral Blood Flow Activation to the Effects of Word Frequency and Word Length

Because our regression analyses showed frequency and length to be reliable predictors of behavioral performance, in terms of RT, our next series of analyses focused on whether rCBF activation was related to the changes in RT as a function of frequency and length and whether this relation differed between the age groups. We used the standardized regression coefficients for word frequency and length from the ANOVA analyses as criterion variables. Our next step was to use the normalized PET counts for the two cortical regions of interest (left BA 17 and left BA 37) as predictors of these frequency and length coefficients. We initially chose these two regions of interest because Madden, Langley, et al. (2002) reported that these were the only two regions that exhibited an age difference in activation. Thus, these regions were a logical starting point to examine the relation between activation and task performance.

Using multiple regression with repeated measures on the scan block variable, we performed separate analyses of the word frequency and length regression coefficients obtained for each participant, in which the normalized PET counts for the local maxima in BAs 17 and 37 were simultaneous predictors.[3] We also included variables representing the main effect of age group and its interaction with each of the predictors (see Table 2 for coefficient and *t* values for each predictor).

The results indicated that when the criterion variable was the standardized regression coefficient for word frequency, there was a significant main effect for age group, as well as significant interactions between age group and the normalized PET counts at both local maxima (the age interaction for BA 37 was marginally significant). In contrast, when the criterion variable was the standardized regression coefficient for word length, only the Age × BA 17 variable reliably predicted the relationship between character length and RT. We therefore followed up these analyses of the word frequency and length data with separate regression equations for younger and older adults, using the PET counts for BAs 17 and 37 as simultaneous independent variables.

Table 2. Multiple Regression Analysis of BAs 17 and 37 and Age Interaction Terms on Frequency and Length Using Simultaneous Entry of Predictors

Predictor	*Coefficient*	*t*	*df*	*p*
Frequency				
BA 17	−.214	1.38	187	.169
BA 37	−.232	1.39	187	.166
Age	−.698	3.17	22	.004
BA 17 × Age	.413	2.67	187	.008
BA 37 × Age	.325	1.94	187	.054
Length				
BA 17	−.169	0.93	187	.353
BA 37	.201	1.02	187	.307
Age	−.453	1.76	22	.093
BA 17 × Age	.409	2.25	187	.025
BA 37 × Age	.046	0.24	187	.812

For younger adults, neither BA 17 nor BA 37 activations predicted the standardized regression coefficients for word frequency (see Figure 3A). For the older adults, however, the PET count values for both BAs 17 and 37 were significant predictors of the word frequency data, with $\beta = -0.627$, $t(93) = 2.83$, $p < .01$, for BA 17, and $\beta = -0.557$, $t(93) = 2.79$, $p < .01$, for BA 37 (see Figure 3B). In each case, the regression coefficients for the PET count variables were negative, indicating that higher levels of rCBF activation were associated with a more negative relation between RT and word frequency (i.e., a more pronounced slowing of the lexical decision response as words decrease in familiarity). When word length coefficients were the criterion variable and BAs 17 and 37 were predictors, neither of the predictors was significant for younger adults (Figure 4A), whereas for older adults, only BA 17 was a significant predictor (see Figure 4B), $\beta = -0.578$, $t(93) = 2.04$, $p < .05$. The regression coefficient in this case was also negative, which reflects stronger activation in BA 17 when RT was less dependent on word length.

It is surprising that that activation in neither BA 17 nor BA 37 was correlated with word frequency coefficients in younger adults, given that word frequency did affect younger adults' behavioral performance (RTs). This null effect might be attributed to our initially analyzing only those cortical areas for which lexical A−baseline counts yielded significant age interactions in voxel counts. That is, although Madden, Langley, et al. (2002) found that

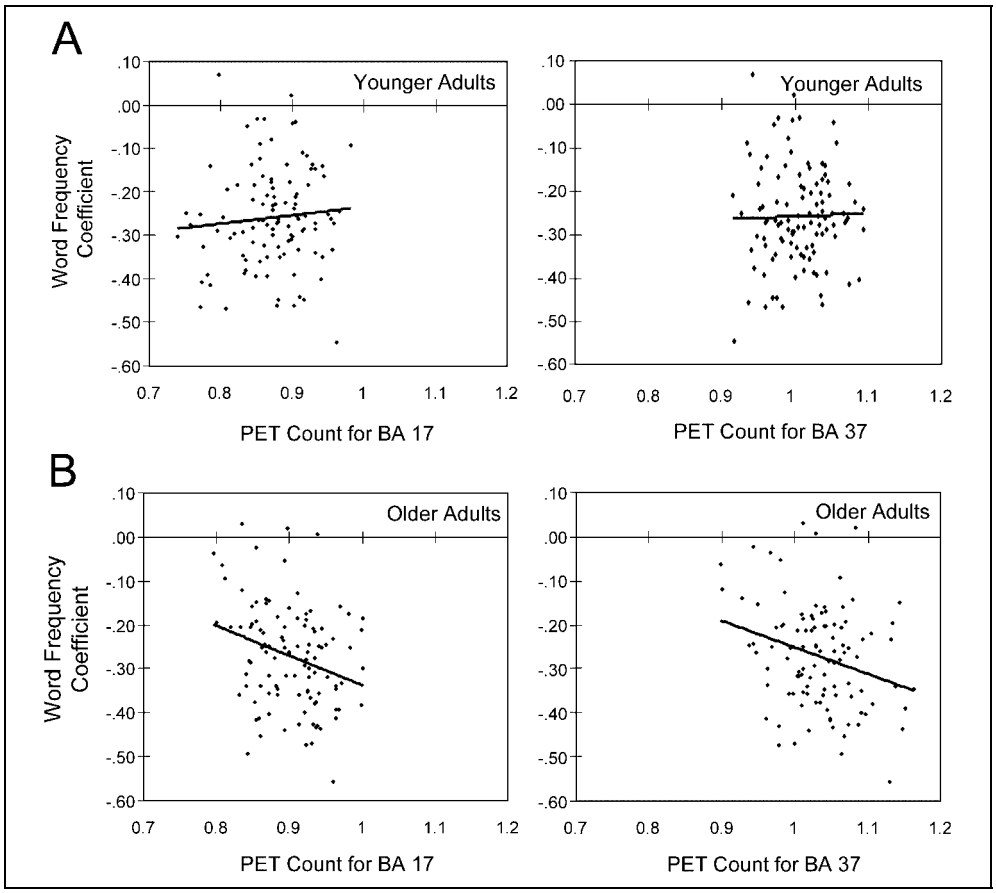

Figure 3. Linear regression of word frequency coefficients and PET activation counts for BAs 17 (left) and 37 (right) for younger (A) and older adults (B).

BAs 17 and 37 were associated with age interactions, these authors also reported other regions (see Figure 1), including local maxima in the left prefrontal inferior cortex, which were associated with activation related to word identification, for both age groups. Thus, we next examined cortical areas of activation within each age group for which there was significant activation in the lexical A–baseline subtraction that did not exhibit age interactions. The activation counts in these areas were then simultaneously regressed onto word frequency coefficients as in previous analyses. These regressions were computed for younger and older adults in separate analyses. For younger adults, these activations included local maxima in BAs 17, 18, 36, and 45 of the left hemisphere only. However, for younger adults, none of these areas was related to word frequency coefficients. For older adults, significant activations were limited to left BAs 18, 44, and 47 for lexical A–baseline subtraction, and of these areas, BA 18 (inferior occipital gyrus) was the only area that showed a significant relationship with word frequency coefficients, $\beta = -1.07$, $t(89) = 11.66$, $p < .01$. None of these areas of activation was correlated with word length coefficients for either age group.

In summary, for older adults, the magnitude of the relationship between word frequency and RT (expressed in regression coefficients) was related to activation levels in BAs 17, 18, and 37 of the left hemisphere, such that stronger relationships were associated with higher levels of activation. Older adults also showed a relationship between word length and BA 17. There was no relationship between word frequency or length coefficients and cortical activation in younger adults.

We cannot determine from these analyses alone whether the older adults' increased cortical activation was driven by their responding more slowly to low-frequency words or by their responding more quickly to high-frequency words. In an attempt to delineate this relationship, we first divided the older participants (using a median split) into two groups, those with higher mean word frequency regression coefficients (reflecting differences in the absolute magnitude of the relation between normative word frequency, in terms of the SFI [Carroll, Davies, & Richman, 1971], and RT) and those with lower coefficients. We then examined whether RT differences between these two subgroups of older adults were greater for higher (50.0–64.9 SFI) or lower (20–34.9 SFI) frequency words. This difference was not significant, $t < 1.0$ (see Figure 5A).

A similar analysis was conducted for subgroups of older adults with higher and lower word length coefficients (created by median split). We compared these two groups of older adults on their RTs for shorter (4–5 characters) and longer words (9–10 characters).

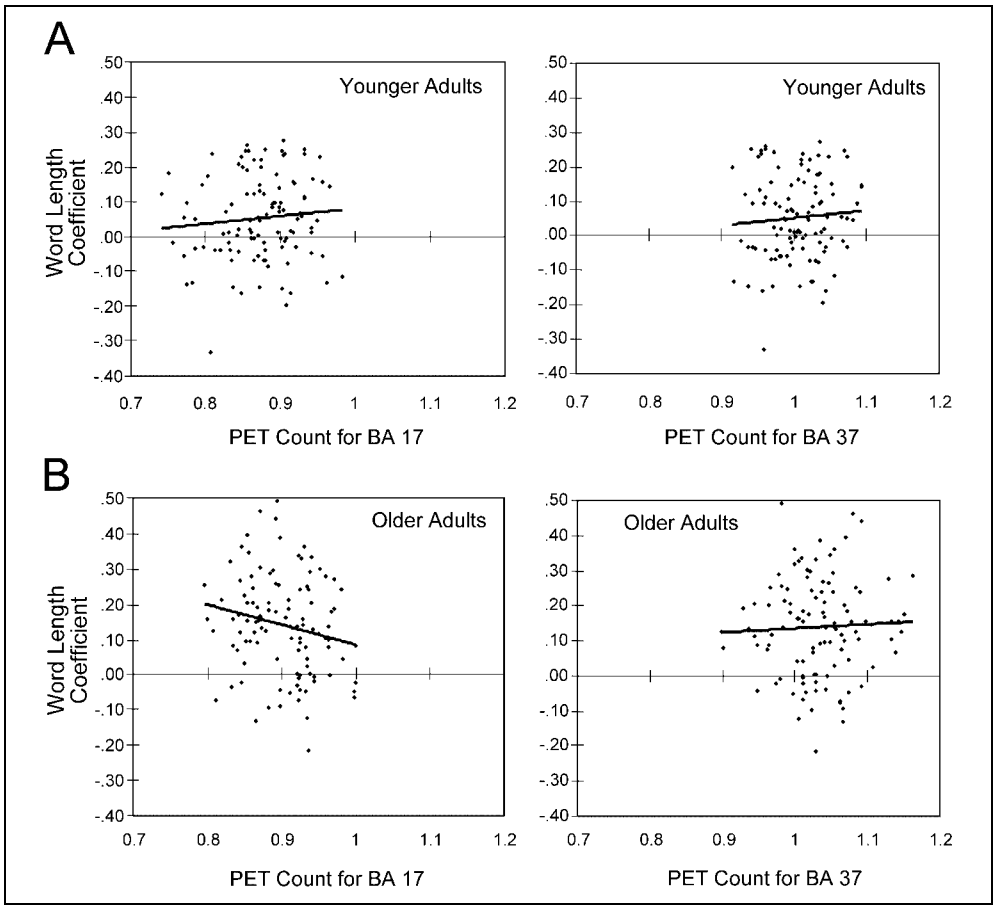

Figure 4. Linear regression of word length coefficients and PET activation counts for BAs 17 (left) and 37 (right) for younger (A) and older adults (B).

We expected that the higher coefficient group would be reliably slower than the lower coefficient group for longer length words, but that group differences would be less apparent for shorter words. The results confirmed our predictions. Mean RT differences between the subgroups of older adults were larger for longer words, $t(10) = 2.41$, $p < .05$, than for shorter words $t(10) < 1$ (see Figure 5B).

DISCUSSION

The results of the behavioral data from both age groups were generally consistent with the results obtained by Spieler and Balota (2000) with a naming task. We found, as did Spieler and Balota, that word frequency accounted for a larger proportion of RT variance in word identification than did word length. Further, frequency regression coefficients were negative whereas length coefficients were positive, indicating slower lexical decision responses to less familiar words and to longer words, respectively. This pattern was similar for younger and older adults, consistent with previous reports of age constancy in semantic memory tasks (Wingfield & Stine-Morrow, 2000; Light, 1996). The converging results of the present study and those of Spieler and Balota suggest that both naming and lexical decision tasks require

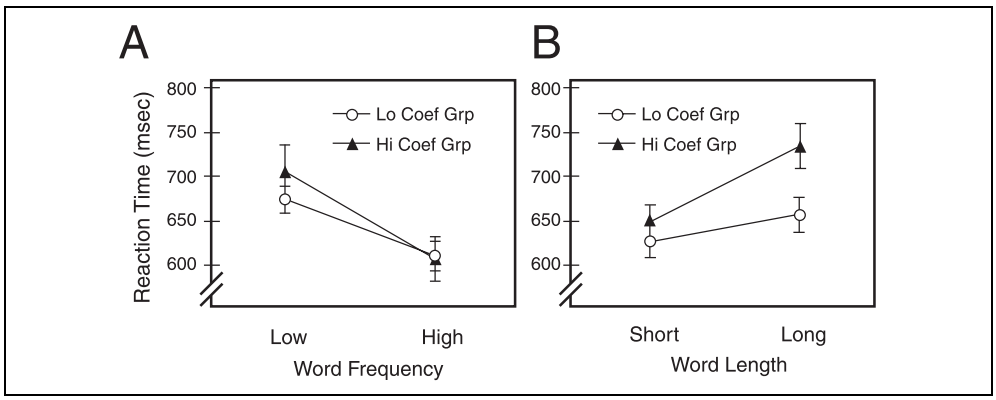

Figure 5. Mean (with standard error bars) lexical decision RTs for low and high coefficient older adult subgroups as a function of word frequency (A) and word length (B).

similar processes of lexical access and that normative word frequency continues to be an important determinant of visual word identification with advancing age. In fact, it is the cumulative frequency of viewing words repeatedly that is thought to contribute to the automatic processing of words and their meanings (Borowsky & Besner, 1993). More generally, both our findings and those of Spieler and Balota demonstrate the value of combining analyses at the item level with those at the participant level (Andrews & Heathcote, 2001).

Despite the general similarities between our findings and those of Spieler and Balota (2000), the pattern of age effects in the behavioral data did differ between the two studies. Specifically, in the present study, word frequency coefficients were similar for younger and older adults, whereas word length coefficients were larger for older adults. In the Spieler and Balota word-naming study, in contrast, there were larger frequency coefficients for older adults relative to younger adults and a trend towards larger length coefficients for younger adults. Thus, our results suggest that, in lexical decision performance, older adults are affected more by sublexical factors in that they require more time to make decisions about longer words, relative to younger adults, but older adults did not rely more on lexical factors (e.g., frequency). Other previous investigations of lexical decision (Allen et al., 1993; Tainturier et al., 1989) have also reported comparable effects of word frequency for younger and older adults, and Allen et al. (1991) found in addition that the effect of word length was relatively greater for older adults. The present findings are consistent with those of Allen et al. and suggest that some of the age-related variance in lexical decision could be due to perceptual encoding difficulties rather than lexical access problems.

The discrepancy between the present findings and those of Spieler and Balota (2000) may be due to task characteristics of word naming and lexical decision. For example, Spieler and Balota used only single-syllable words ranging from 2 to 7 letters, whereas the words in the present study consisted of both single and multisyllabic words that ranged in length from 4 to 10 letters. The use of words of longer lengths (and thus greater perceptual load) in the present study may have contributed to the different effects of length on RT for older adults relative to younger adults. In addition, in our lexical decision task, frequency accounted for approximately twice the amount of RT variance (15.7%) than that reported in Spieler and Balota's (2000) naming study (7.7%). In a study comparing both naming and lexical decision tasks, Andrews and Heathcote (2001) also found that frequency effects in lexical decision were roughly twice as large compared to word naming, which may represent the contribution of familiarity-based responding in lexical decision (Balota & Chumbley, 1984). Thus, older adults may rely more on lexical variables when familiarity plays a less prominent role in task performance, as in word naming.

An important contribution of this study to research on word identification and neuroimaging is the examination of the lexical and sublexical effects, because no other study has investigated how these component mechanisms of word identification correlate with activation levels. The most striking effects in this study resulted from using voxel counts in the left occipito-temporal pathway—the striate (BA 17), inferior occipital (BA 18), and inferior temporal cortex (BA 37)—to predict word frequency and length. With respect to word frequency, only older adults' (as opposed to younger adults') voxel counts at local maxima in BAs 17, 18, and 37 of the left occipito-temporal pathway were significant predictors of word frequency coefficients. The negative word frequency coefficient/activation slopes for older adults indicate that a greater degree of word identification slowing in response to decreasing word familiarity was associated with increased activation in BAs 17, 18, and 37 of the left hemisphere (see Figure 3B). That is, activation in these areas may reflect older adults' greater reliance on neural architecture for lexical-based processing to correctly and quickly identify words. One possibility is that this relationship may be driven primarily by slower responses to lower frequency words, although this trend was not statistically significant in the one analysis used to test this interpretation (see Figure 5A).

Previous studies have implicated regions within the inferior temporal lobe as modulating both word form (orthographic) processing (e.g., Dehaene et al., 2002; Polk & Farah, 2002) and semantic processing (see Binder & Price, 2001; Martin, 2001, for reviews). The fact that lexical factors (i.e., word frequency) were related to activation in the inferior temporal lobe (BA 37) in older adults suggests that this area may be involved in lexical access. This pattern of activation replicates previous neuroimaging studies that have shown left inferior temporal activation during other semantic tasks such as object naming (Zelkowicz, Herbster, Nebes, Mintun, & Becker, 1998; Martin, Wiggs, Ungerleider, & Haxby, 1996; Bookheimer, Zeffiro, Blaxton, Gaillard, & Theodore, 1995) and semantic decision (Chee et al., 1999; Price, Moore, Humphreys, & Wise, 1997). In the present study, older adults' greater activation (relative to younger adults) in the inferior temporal lobe is consistent with Grady et al.'s (1994) similar finding of relatively greater anterior activation in this area for older adults during a face-matching task. Taken together, these findings suggest that older adults' may process information further down the visual processing stream where semantic processing is more likely to be engaged.

It is interesting that BA 17 activation in older adults was also correlated with lexical properties (i.e., frequency), because this cortical region is the primary visual sensory area. This relationship might best be explained in light of Balota and Chumbley's (1984) argument that lexical decisions are based, in part, on orthographic familiarity. That is, the more often a word is seen in printed text

(word frequency), the more familiar the visual characteristics of the word become, thus biasing responding toward ''word'' responses. If this familiarity mechanism has a substantial visual component (i.e., word shape), then it is reasonable that this mechanism would involve the sensory processing regions of the left occipitotemporal pathway. Further, if familiar orthographic representations are formed only after significant experience or time, it would not be surprising to see such relationships in older but not younger adults. Thus, it is possible that the BAs 37 and 17/18 activations, in response to word frequency, represent different forms of lexical processing. Nevertheless, both of these forms of lexical processing would appear to be heavily dependent on age. That is, as we age, words become orthographically more familiar thus contributing to the relationship between visual cortex activation and word frequency. Similarly, with age, the number of semantic representations associated with words also increases (cf. Burke et al., 2000), thus shedding light on why older adults relied more on word frequency at least at the neural level.

The absence of any relation, in these data, between word frequency and left prefrontal activation is surprising, in view of the frequently observed association between semantic processing and activation of left prefrontal cortical regions (Binder & Price, 2001; Kanwisher et al., 2001). Because subregions of the left prefrontal cortex appear to primarily support phonological processing (Fiez, 1997), it is possible that the left prefrontal activation in these data represent the use of phonological mechanisms (e.g., subvocal pronunciation of the words and nonwords) not related specifically to lexical access. Alternatively, the small sample size may have limited the statistical power to detect the relations to lexical and semantic retrieval that do exist. Another intriguing possibility, although speculative, is that the left prefrontal activation that is often observed during semantic tasks represents a ''retrieval mode'' for the initiation and effort of retrieval, rather than the access of specific information (Nyberg et al., 1995).

Activation in left BA 17 also predicted word length coefficients in older adults, such that higher levels of activation were associated with less dependence of the lexical decision RTs on word length (see Figure 5B). Finding relationships between sublexical word properties (e.g., word length) and occipital activation is consistent with a previous study by Puce, Allison, Asgari, Gore, and McCarthy (1996) in which the left inferior occipital gyrus (BA 18) was implicated in the processing of letter features. Thus, it would appear that more elementary aspects of word identification take place in the more ventral and posterior regions of the occipitotemporal pathway, and that in the present study, sublexical features such as word length are also processed in the more posterior regions of this pathway.

One interesting finding of this study was that efficiency in lexical and sublexical processing lead to opposing patterns of activation in older adults. In the present task, we interpret smaller regression coefficients as representing greater processing efficiency, because smaller coefficients reflect less dependence of RT on variation in word frequency and length. We found that smaller coefficients for word frequency were associated with lower activation in BAs 17, 18, and 37, suggesting that more efficient lexical processing was reflected in decreased neural activity in these regions. In contrast, smaller word length coefficients were associated with increased activation in BA 17, indicating that efficient sublexical processing is associated with higher levels of activation. Consequently, the higher coefficients for word length (driven by slower responses to longer words), associated with decreased activation in BA 17, may represent perceptual processing difficulties in older adults. These contrasting patterns of activation suggest a distinction between the neural architecture supporting older adults' lexical and sublexical processing.

Despite the fact that younger adults clearly use frequency for word identification, as indicated by raw RT regressions (see Table 1), no significant relation between the frequency coefficients and activation levels was detected in the regression analyses for younger adults. Thus, the neural mechanisms mediating the relationship between RT and the components of word identification for younger adults remain unclear. Younger adults' activation may be related to task performance variables other than frequency and length, or, as noted previously, there may have been insufficient statistical power to detect relations among variables that do exist. Our findings, however, are consistent with analyses of other cognitive tasks indicating that age-related changes exist in the relation between neural activation and behavioral performance (Madden, Turkington, et al., 2002; Rypma & D'Esposito, 2000). Additional research with imaging methods better suited than PET to identify activation associated with individual stimuli, such as event-related function magnetic resonance imaging, will be particularly helpful in this regard.

In summary, the results indicate that although word frequency and length were important predictors of word identification performance for both older and younger adults, the neural mechanisms mediating the processing of these task components differed as a function of age group. Only for the older adults were the frequency and length variables associated with changes in brain activation. Although it is unclear what specific role word frequency and length may play in mediating older adults' activation levels during word identification, we suggest that the aging process generally increases both the orthographic familiarity and semantic representations associated with particular words resulting in a greater reliance on neural areas supporting these lexical functions during word identification. The increased reliance on these neural regions may help explain why behavioral measures of lexical word processing, and

semantic memory in general, are maintained with age. It is also apparent from the data that older adults' lexical decision responses were differentially slowed by increasing word length, and this pattern was associated with decreased visual cortex activation. Thus, although lexical aspects of words may be maintained age and experience, visual sensory declines with age may place limits on word identification efficiency in older adults.

METHODS

Participants

The research procedures were approved by the Institutional Review Board of the Duke University Medical Center, and all participants gave written informed consent. Twelve younger adults between 20 and 29 years of age (M = 23.58 years) and 12 older adults between 62 and 70 years of age (M = 65.0 years) participated. All were healthy, right-handed, community-dwelling individuals; there were six women in each age group. All participants possessed at least a high school education, corrected visual acuity for near point of at least 20/40, and scored at least 27 (out of 30) on the Mini-Mental State Exam (Folstein, Folstein, & McHugh, 1975). The raw score on the Vocabulary subtest of the Wechsler Adult Intelligence Scale—Revised (Wechsler, 1981) was comparable for the younger adults (M = 63.25) and older adults (M = 63.92).

Apparatus, Stimuli, and Procedure

During the 12 PET scans, participants performed a series of trials, each of which required a yes/no decision regarding a single string of visually presented letters (the target). Participants viewed the targets on a computer monitor suspended above the scanner gantry and responded by means of a two-button response box. The targets were presented as white letters against a dark gray background. The targets were approximately 0.90° in height and ranged in width from 2.69° (4 letters) to 6.71° (10 letters). Participants rested the index and middle fingers of the right hand on the two response buttons (counterbalanced across participants).

There were four task conditions performed during separate PET scans. One of the conditions was a baseline task (simple visual search, for the presence of a lowercase *c* among alternating capital *T*s and *Z*s) and the other three of which involved word/nonword discrimination (lexical decision). In the lexical decision conditions, participants responded *yes* when the target was a word and *no* when it was a nonword. The conditions differed in the duration and presentation rate of the targets. Each trial began with a 500-msec warning signal (asterisk). In the baseline condition, target duration was 750 msec and the interstimulus interval (ISI) was 750 msec, yielding a target presentation rate of one target per 2000 msec. The same values were used for the lexical A condition. In the lexical B condition, target duration was 375 msec and the ISI was 1125 msec, and thus presentation rate was one target per 2000 msec. In the lexical C condition, target duration was 375 msec and the ISI was 750 msec, yielding a presentation rate of one target per 1625 msec. RT for the yes/no response was measured from target onset.

The present analyses focused exclusively on the three lexical decision conditions. The complete sample of targets for the lexical decision conditions contained 720 words and 720 nonwords. The words were selected to have their primary usage as a noun, with a standard SFI value (Carroll et al., 1971) between 20 and 65. (Increasing SFI represents increasing frequency of occurrence in printed text.) All of the nonwords were pronounceable but nonhomophonic with real words. These items were grouped into 12 sets of 60 words and 12 sets of 60 nonwords, such that within each set, the length of the targets ranged from 4 to 10 letters. Across the 24 sets of 60 items, mean target length per set ranged from 6.75 to 6.95 letters. Across the 12 sets of words, the mean SFI ranged from 41.69 to 42.20. In the lexical A and B conditions, each trial block contained 120 trials, comprising one set of words and one set of nonwords, ordered randomly. In the lexical C condition, which used the highest rate of target presentation, each of the trial blocks contained 240 trials, comprising four of the 60-item sets (two sets of words and two sets of nonwords).

The PET testing session began with practice trials for each of the task conditions. The experimenter instructed participants to respond as quickly as possible while maintaining accuracy. Within the testing session of 12 blocks of trials, a particular sequence of the four task conditions was repeated three times. The complete set of trials viewed by an individual participant contained one instance of each word and nonword target.

Positron Emission Tomography

The PET methodology was estimation of rCBF from radioactivity counts, following intravenous bolus injection of $H_2{}^{15}O$. Imaging was conducted in the 3-D (septa out) mode, with a General Electric Advance whole-body PET scanner containing 18 detector rings (DeGrado et al., 1994). Data were acquired simultaneously from 35 imaging planes (18 direct planes and 17 cross planes) separated by 4.25 mm. The axial field of view was 15 cm, and the intrinsic in-plane and axial spatial resolutions were approximately 5 mm full width half maximum (FWHM). A transmission scan was performed for attenuation correction. During the emission scans, radiotracer injection (10 mCi) was performed through an intravenous catheter placed in the participant's left arm, at the beginning of the testing session. Presentation of the trial sequence began 30–60 sec prior to radiotracer injection and continued for approximately 4–6.5 min, depending on the task condition. Successive

PET scans were separated by 10 min to permit radioactivity decay. After correction for attenuation, scatter, randoms, and dead time, image reconstruction was performed with a filtered back-projection (Kinahan & Rogers, 1990) using a Hann filter transaxially and a ramp filter axially.

For this data set, Madden, Langley, et al. (2002) reported analyses of the differences in rCBF activation between pairs of task conditions, using Statistical Parametric Mapping (SPM99, Wellcome Department of Cognitive Neurology, London, UK; Friston et al., 1995). The SPM analyses involved realignment of the scans, normalization and transformation into a standard stereotaxic space (Talairach & Tournoux, 1988), and additional smoothing with a 15-mm FWHM isotropic Gaussian kernel. Using a fixed effects model, an analysis of covariance was applied to the PET counts on a voxel by voxel basis, including global activity as a confounding covariate, thresholding for height at $Z = 2.33$ ($p = .01$, uncorrected). Voxel-level rCBF change was considered statistically significant if the corrected probability level for the peak height of the local maximum was less than .05. A masking analysis was used to identify from those voxels that were significantly activated for a particular age group (at $p < .05$, corrected) the subset of voxels that exhibited a greater degree of change in activation than in the other age group.

The Madden, Langley, et al. (2002) SPM analyses indicated that for the lexical A–baseline contrast, age-related change in activation was restricted to two local maxima in the left hemisphere (Figure 1), the striate (BA 17; $x = -22$, $y = -102$, $z = -2$) and inferior temporal region (BA 37; $x = -54, y = -52, z = -15$). In this contrast, the lexical and baseline conditions were matched for display duration and presentation rate. The present analyses were concerned with changes in RT to the word targets in the lexical decision condition, as a function of word frequency (SFI) and length (number of letters), in relation to rCBF activation at these two local maxima. The rCBF data were the PET radioactivity counts for these two local maxima, obtained for each combination of participant and task condition. The PET counts represent the tissue concentration of $H_2{}^{15}O$ and are a nearly linear function of quantitative changes in rCBF as determined from arterial blood sampling (Herscovitch, Markham, & Raichle, 1983). The count values were normalized to the participant's whole-brain gray matter mean value (average of all voxels above 80% of the mean voxel value for the entire brain image) in the corresponding task condition.

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Notes

1. Spieler and Balota (2000) also used Coltheart's *N*, an estimation of neighborhood density, as a sublexical predictor of word naming RT. This variable reflects the number of similarly spelled words adjacent to the target word. Because Spieler and Balota found that Coltheart's *N* was weaker than both word frequency and length as a predictor of word naming RT for both age groups, it was not included in the present study.
2. Lexical task condition variables (i.e., the main effect of condition and the interaction term with frequency and length) were initially entered into this equation. However, none of the condition variables were significant predictors in the equation, and are thus not included in this equation.
3. Although we selected the local maxima at BAs 17 and 37 based on the lexical A–baseline contrast, to maximize statistical power, we included the PET counts from all three lexical conditions in the analyses of the relation between activation and RT (i.e., lexical A, B, and C). The duration and presentation rate of the stimuli were varied across the three lexical conditions. However, each condition involved a series of word/nonword discriminations of individual letter strings. The Madden, Langley, et al. (2002) data indicated that the changes in rCBF activation across the three lexical conditions were minimal and were not associated with age differences. Variables representing the different lexical task conditions were initially entered simultaneously with the predictors listed in Table 2, but none of these condition variables were significant predictors. Consequently, the lexical condition variables were not included in the final analysis presented in Table 2.

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