

Age-related Differences in the Neural Bases of Phonological and Semantic Processes

Michele T. Diaz¹, Micah A. Johnson¹, Deborah M. Burke²,
and David J. Madden¹

Abstract

■ Changes in language functions during normal aging are greater for phonological compared with semantic processes. To investigate the behavioral and neural basis for these age-related differences, we used fMRI to examine younger and older adults who made semantic and phonological decisions about pictures. The behavioral performance of older adults was less accurate and less efficient than younger adults' in the phonological task but did not differ in the semantic task. In the fMRI analyses, the semantic task activated left-hemisphere language regions, and the phonological task activated bilateral cingulate and ventral precuneus.

Age-related effects were widespread throughout the brain and most often expressed as greater activation for older adults. Activation was greater for younger compared with older adults in ventral brain regions involved in visual and object processing. Although there was not a significant Age × Condition interaction in the whole-brain fMRI results, correlations examining the relationship between behavior and fMRI activation were stronger for younger compared with older adults. Our results suggest that the relationship between behavior and neural activation declines with age, and this may underlie some of the observed declines in performance. ■

INTRODUCTION

Although decline in cognitive functions is often observed with aging in later adulthood, language functions show a pattern of both impaired and spared performance. Semantic processes are well maintained during adulthood, for example, indices of semantic retrieval, such as vocabulary, increase with age (Verhaeghen, 2003; Alwin & McCammon, 2001) until 80 years or beyond (Schaie, 2005; Singer, Verhaeghen, Ghisletta, Lindenberger, & Baltes, 2003; Lindenberger & Baltes, 1997). Younger and older adults demonstrate comparable semantic organization in producing word associations (Burke & Peters, 1986; Bowles, Williams, & Poon, 1983), category members (Howard, 1980), typicality judgments (Little, Prentice, & Wingfield, 2004), semantic priming effects (Madden, Pierce, & Allen, 1993; Bowles, 1989; Burke, Peters, & Harrold, 1987), and metaphor comprehension (Light, Owens, Mahoney, & LaVoie, 1993). The preservation of semantic functions in normal aging is even more impressive because it occurs despite age-related decline in neuroimaging measures of brain structure for both gray and white matter (Madden et al., 2012; Salat, 2011; Fjell & Walhovd, 2010; Raz, 2005).

In contrast to semantic processing, however, older adults show impairments in phonological retrieval. For example, older adults demonstrate increased slips of the tongue (MacKay & James, 2004), more omitted phonemes in

tongue twisters (Taylor & Burke, 2000), and a tendency to insert more pauses in speech (Vousden & Maylor, 2006). Older adults also show increased tip of the tongue (TOT) experiences in which individuals have a vivid sense of knowing the word, can produce its meaning, but are temporarily unable to produce the word itself (Burke, Mackay, Worthley, & Wade, 1991). Considerable research suggests that TOT experiences are caused by a failure to retrieve a word's phonology (White & Abrams, 2002; James & Burke, 2000) and age-related deficits in phonological retrieval processes lead to an increase in TOTs during older adulthood (see Burke & Shafto, 2008, for a review). The asymmetric pattern of age-related differences in semantic and phonological processes suggests a fundamental difference in the cognitive and neural organization of these two language abilities and that these processes are at least partially dissociable.

Functional neuroimaging studies suggest that the pattern of age-related differences in behavioral measures of semantic and phonological processes correspond to age differences in regional neural activation. Several aging studies that have examined the neural correlates of phonological processes (see Burke & Graham, 2012, for a review) have used TOT tasks to examine neural activation during phonological retrieval failure. Shafto, Stamatakis, Tam, and Tyler (2010) reported that TOT states, induced in a picture naming paradigm, engaged bilateral insula. Moreover, in both regions older, but not younger, adults showed a negative correlation between functional activation and TOT frequency. These results suggest that the

¹Duke University Medical Center, ²Pomona College

older adults who elicited greater levels of activation (similar to levels observed in younger adults) have fewer incidences of failed retrieval.

Some researchers have interpreted increased activation in older adults that is associated with equivalent or improved behavioral performance as compensation. Evidence consistent with compensation has been found in several cognitive domains, especially episodic and working memory (Wierenga et al., 2008; Cabeza, Anderson, Locantore, & McIntosh, 2002; Reuter-Lorenz et al., 2000) and also in some highly lateralized language functions such as syntax (Pelle, Troiani, Wingfield, & Grossman, 2010; Tyler et al., 2010). However, increases in activation have not always been correlated with improved or maintained behavior in other cognitive domains (Loibl, Beutling, Kaza, & Lotze, 2011; Meinzer et al., 2009; Riecker et al., 2006; Logan, Sanders, Snyder, Morris, & Buckner, 2002).

In a study testing both semantic and phonological processes, Shafto and colleagues used auditory lexical decision to examine the effects on functional activation of imageability (a semantic aspect) and cohort size (a phonological aspect) of the words (Shafto, Randall, Stamatakis, Wright, & Tyler, 2012). Behaviorally, both younger and older adults responded more quickly to words with higher imageability, and older but not younger adults showed greater activation in left middle and superior temporal gyri for words lower in imageability. These results are consistent with a compensatory interpretation in which older adults maintain semantic processes via greater neural activation. However, other studies have reported age constancy in performance on semantic judgments with no age differences in activation (Daselaar, Veltman, Rombouts, Raaijmakers, & Jonker, 2003; Stebbins et al., 2002; Johnson et al., 2001).

Shafto et al. (2012) also reported that younger but not older adults responded more slowly to words with larger phonological cohorts and showed increased activity in left inferior frontal gyrus (IFG) for these words. The older adults' deficits in phonological processing are reflected in the insensitivity of their behavioral and neural responses to phonological variation. That is, words with larger phonological cohorts should be more difficult to process because there are more phonological competitors, and older adults showed less sensitivity to this variable. The Shafto et al. (2012) results are consistent with age-related compensation in the semantic domain but not the phonological domain. However, Geva and colleagues reported that older adults had increased activation in right inferior frontal regions and equivalent behavioral performance during a rhyme judgment, which would be consistent with compensation in the phonological domain (Geva et al., 2012). Thus, there remains some inconsistency relating fMRI results to behavioral performance in tasks requiring phonological analyses. Moreover, many studies to date have focused on single aspects of language processing or compared different aspects of language processing using different stimuli.

This study is the first to compare younger and older adults' performance and neural response for both semantic and phonological judgments about the same stimuli. Participants were presented with a question about a phonological property (e.g., starts with B?) or a semantic property (e.g., combustible?) followed by photographs of two objects to which they responded.¹ We included photos as opposed to auditory or lexical stimuli to limit the influence of orthographic or phonological perceptual input on retrieval. We predicted that age-related behavioral differences would occur in the difficulty (speed and/or accuracy) of phonological but not semantic decisions. Second, we predicted that age-related differences in the pattern of neural response would be greater for phonological than semantic decisions. Finally, we examined age differences in the relation between neural mechanisms and behavior and how these relationships may differ across conditions. Specifically, we examined the results for patterns of compensation or inefficiency in older adults. Increases in activation for older adults that correspond to maintained or improved behavior would be consistent with a compensation account. Weaker or no relation between fMRI activation and behavioral performance in older adults would be consistent with neural inefficiency. In either scenario, we predicted that younger adults would demonstrate a relation between neural activation and performance.

METHODS

Participants

All participants were community-dwelling, right-handed, native English speakers. There were 16 younger adults (M age = 23.5 years; age range = 18–35 years; eight men) and 16 older adults (M age = 68.2 years; age range = 61–74; eight men). All participants had normal or corrected-to-normal vision, none reported a history of neurological or psychological disorders, none reported any major medical conditions (e.g., diabetes, heart disease), and none were taking any medication that might affect the brain or blood flow. All participants underwent neuropsychological testing to assess basic cognitive skills such as speed, memory, executive function, and language. Demographic characteristics and scores from neuropsychological assessments are presented in Table 1. Each participant provided informed consent and was paid for his or her participation. All experimental procedures were approved by the Duke University Medical Center institutional review board.

Stimuli

On each trial, participants made one of three types of judgments: phonological, semantic, or perceptual (a control condition). Figure 1 provides an overview of the task design. Stimuli consisted of a cue (semantic, phonological, or perceptual) followed by a pair of photographs of objects.

Table 1. Participant Demographics

	Younger	Older
<i>n</i>	16	16
Age ^a	23.50 (4.62)	68.25 (3.36)
Education	15.88 (2.42)	16.44 (2.06)
MMSE	29.44 (0.73)	28.94 (1.12)
BDI	1.38 (2.13)	1.00 (1.83)
Vocabulary (WAIS II) ^a	55.00 (4.37)	62.75 (4.74)
Verbal fluency (total) ^a	77.56 (20.45)	63.06 (16.97)
Digit symbol RT ^a	1169.74 (154.77)	1924.04 (366.35)
Stroop RT ^a	432.11 (63.68)	641.10 (84.64)
Speed RT ^a	268.27 (29.18)	387.55 (75.20)
Immediate recall ^a	12.50 (2.03)	9.56 (2.48)
Delayed recall ^a	11.31 (2.06)	7.75 (2.89)

Values provided are means, with standard deviation in parentheses.

^aDenotes a statistically significant difference.

Cues were a word or short statement followed by a question mark. Semantic cues presented a question about a functional or perceptual attribute of the objects (e.g., Smooth?, Flies?, Edible?). Phonological cues presented a question about the first letter of the object names (e.g., Starts with B?, Starts with P?). Perceptual cues always presented a question about whether the two items were identical (e.g., Same?). Photographs were high-resolution images of everyday objects against a white background. Across conditions, the names of objects did not statistically differ in length (number of letters; phonological match = 5.50; phonological nonmatch = 5.56; semantic match = 5.51; semantic nonmatch = 5.59), number of syllables (phonological match = 1.58; phonological nonmatch = 1.65; semantic match = 1.62; semantic nonmatch = 1.65), number of phonemes (phonological match = 4.52; phonological nonmatch = 5.02; semantic match = 4.57; semantic nonmatch = 4.64), and word frequency (phonological match = 37.32; phonological nonmatch = 32.20; semantic match = 31.40; semantic nonmatch = 35.17). Although not a phonological feature per se, frequency was controlled because of its well-established influence on naming (e.g., Oldfield & Wingfield, 1965). Ratings of stimulus properties were obtained from the English Lexicon Project (Balota et al., 2007).

During fMRI scanning, the entire experiment comprised 240 trials, with 80 trials (40 match, 40 nonmatch) in each of the three judgment conditions. Individual objects occurred once for each participant but were counterbalanced across the semantic and phonological conditions across participants, with two separate trial lists. We created images for the perceptual judgments in Matlab (The MathWorks, Natick, MA) by applying a Fourier transform to a random

subset of the object photographs, permuting the phase spectrum, and then computing an inverse transform. We then adjusted the luminance of the perceptual photographs to match the original photograph. This procedure yielded displays that contained the basic perceptual features of the original photographs, but the features did not combine to form a recognizable object.

Stimulus Pretesting

In developing the final experimental stimuli, we conducted two behavioral pretests to validate the stimulus set. The first pretest was conducted to evaluate the consistency in picture naming. An independent group of 15 healthy, native English-speaking younger adults participated in the first pilot study (*M* age = 23.5 years, range = 19–33 years, eight women). Participants were asked to name 545 color photos that depicted a wide range of common objects. Items were included for possible further selection if naming consistency was 93% or better (i.e., 14 of 15 responses concurred). Although participants were not asked to explicitly name the items in the main experiment, they would need to recall the name to perform the phonological task and were likely naming the items in the semantic task.

The second behavioral pretest was conducted to evaluate the task itself to ensure that participants' responses were consistent with our coding. A second independent group of 13 healthy, native English-speaking younger adults participated in the second pilot study (*M* age = 23.38 years, range = 18–31 years, four women). The experimental procedure was similar to the final task. Participants were shown a semantic or phonological cue,

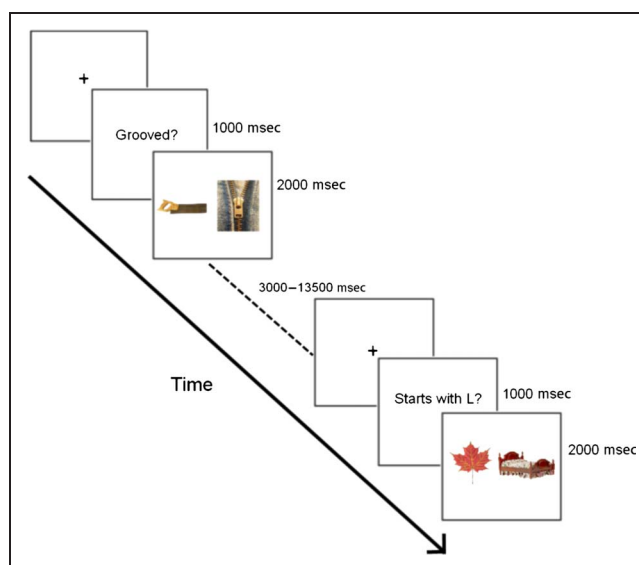


Figure 1. Task design. An overview of the task design is provided. Here we highlight two typical trials (semantic and then phonological). Cues were presented for 1 sec followed by pictures which were presented for 2 sec. The ISI was jittered between 3 and 13.5 sec with a mean interval of 4.8 sec.

followed by a pair of photographs, and they responded whether both items matched the cue or not. Participants viewed 170 semantic trials and 170 phonological trials. Pairs were included in the final stimulus set if the concordance between participants' responses and the intended response exceeded 70% across participants. The final stimulus set included items for which there were no statistically significant differences in RT [semantic trials $M (SD) = 1620$ msec (251 msec); phonological trials $M (SD) = 1643$ msec (309 msec); $t = 0.58$, $df = 198$, $p = .56$]. No participants from either of these pretest participated in the main experiment.

Behavioral Pretesting

Before the fMRI testing (typically by 1–2 weeks), all participants completed a 2-hr screening session, which included psychometric and visual sensory tests (Table 1). Participants were screened for contraindications to scanning and factors known to influence functional imaging of language (e.g., handedness, language history). The testing also included a practice version of the cognitive task to be performed during the fMRI session and a naming task to ensure that all participants could name the object stimuli.

Experimental Task

Each trial consisted of a cue (duration = 1 sec) followed by two photographs of objects presented side by side (duration = 2 sec). The two objects either both matched the cue or one item was incongruent with the cue. Participants made their match/nonmatch response manually after the onset of the object photographs. The three conditions, phonological, semantic, or perceptual, combined orthogonally with match/nonmatch to yield six different trial types (Figure 1). All six trial types were presented in a randomized order within each fMRI run, with a variable intertrial (interval = 3–13.5 sec, $M = 4.8$ sec). Trial order across conditions and intertrial interval were randomized and optimized using the Optseq2 program (Dale, 1999). A fixation cross was presented at the beginning and the end of each run and was also presented during the variable interval between each trial. All stimuli were presented via a projector using an in-house experimental control program (Voyvodic, 1999). Responses were recorded with a hand-held fiber-optic response box (Current Designs, Philadelphia, PA).

Acquisition of MRI Data

MRI scanning was completed on a 3.0-T GE EXCITE HD whole-body 60 cm bore human scanner equipped with 40 mT/m gradients and a 150 T/m/sec slew rate. An eight-channel head coil was used for radio frequency reception (General Electric, Milwaukee, WI). Sagittal T1 weighted

localizer images were acquired and used to define a volume for data collection and high-order shimming. The anterior and posterior commissures were identified for slice selection and shimming. A semiautomated high-order shimming program was used to ensure global field homogeneity. High-resolution structural images were acquired using a 3-D fSPGR pulse sequence (repetition time [TR] = 7.49 msec; echo time = 2.98 msec; TI = 450 msec; field of view = 25.6 cm²; flip angle = 12°; voxel size = 1 × 1 × 1 mm; 166 contiguous slices). Functional images sensitive to BOLD contrast were acquired using an inverse spiral pulse sequence with SENSE acceleration (TR = 1.5 sec; echo time = 30 msec; field of view = 25.6 cm²; flip angle = 60°; SENSE factor = 2; voxel size = 4 mm³; 30 contiguous oblique axial slices, parallel to the AC–PC line, interleaved acquisition). Each of the eight runs consisted of the acquisition of a time series of 168 brain volumes. Four initial RF excitations were performed to achieve steady-state equilibrium and were subsequently discarded. These factors resulted in individual functional runs that were 4.3 min each.

fMRI Data Analysis

Data were analyzed for quality via a quality assurance tool that quantifies several metrics including signal-to-noise, signal-fluctuation-to-noise, motion, and voxel-wise standard deviation measurements (Glover et al., 2012; Friedman & Glover, 2006). Additionally, all data were visually inspected for artifacts and blurring. The average movement in the x , y , or z directions was 0.15 mm (range = 0.03–0.85 mm). Thus, none of the included participants exhibited more than 1 mm movement in the x , y , or z dimensions. We used FSL version 4.1.5 and FEAT version 5.98 for preprocessing and for all analyses of functional activations (Woolrich et al., 2009; Smith et al., 2004). Prewhitening or voxel-wise temporal autocorrelation was estimated and corrected using FILM (FMRIB's Improved Linear Model; Woolrich, Ripley, Brady, & Smith, 2001). The skull and other coverings were stripped from the structural brain images using the FSL brain extraction tool (Smith, 2002). Functional image data were corrected for slice timing using sinc interpolation to shift each slice in time to the middle of the TR period. Functional images were motion-corrected using FSL's MC-FLIRT (FMRIB's Linear Image Registration Tool) using six rigid-body transformations (Jenkinson, Bannister, Brady, & Smith, 2002). These estimates of motion were included as nuisance covariates in the overall FSL model. Functional data were also high-pass filtered (cutoff = 50 sec) and spatially smoothed using a Gaussian kernel (FWHM = 8 mm). Functional images of each participant were coregistered to structural images in native space, and structural images were normalized to Montreal Neurological Institute (MNI) standard space using FSL's MNI Avg152 T1 2 × 2 × 2 mm standard brain. The same transformation matrices used for structural-to-standard transformations were then used for functional-to-standard space transformations of coregistered functional images.

Coregistration and normalization steps were completed using a combination of affine and nonlinear registrations (Greve & Fischl, 2009; Jenkinson et al., 2002; Jenkinson & Smith, 2001).

We used a double γ function to model the hemodynamic response for each trial. Correct trials were modeled by condition and errors (incorrect responses and omitted responses) were modeled as a separate regressor. RT outliers were defined as responses <250 msec or >3 SD from that individual's overall mean. This resulted in approximately 8% of the trials being excluded (7% incorrect response, 0.61% no response, 0.68% outliers). We combined the analyses from each experimental run and performed an analysis across runs for each participant individually. We then combined these analyses across all participants in group-level analyses using the FMRIB Local Analysis of Mixed Effects (FLAME 1 and 2; Woolrich, Behrens, Beckman, Jenkinson, & Smith, 2004; Beckmann, Jenkinson, & Smith, 2003). Our primary analytic goal was to identify regions that were responsive to our experimental manipulation (semantic and phonological processing), to identify regions where older and younger adults differed, and to detect regions in which the activation differed as a function of both age group and task condition concurrently (i.e., interaction). To accomplish this, we performed a two-way ANOVA within FSL with Condition (Phonological, Semantic), Age Group (Younger, Older), and the interaction of Condition \times Age Group as independent variables. Within FSL, we also made comparisons between conditions to identify differences in functional activation between levels of each variable (e.g., Phonological $>$ Semantic, Semantic $>$ Phonological). All significant activations were determined using a two-step process in which voxels, significant at $p < .01$, were identified. Clusters of identified voxels were then corrected for multiple comparisons according to Gaussian random fields theory ($p < .05$, corrected) in which each cluster's estimated significance level was compared with the cluster probability threshold, and then only clusters whose esti-

mated significance exceeded the threshold were included in the results (Hayasaka & Nichols, 2003). Results from comparisons between conditions (e.g., semantic $>$ phonological) were masked by results from more basic analyses (e.g., semantic $>$ implicit baseline) to ensure that only differences based on significant positive responses were included in the analyses. All analyses involved a whole-brain approach with single comparisons, and thus, the comparisons should not be statistically biased (Kriegeskorte, Simmons, Bellgowan, & Baker, 2009). All reported regions were identified through the use of the Harvard-Oxford Atlas (Desikan et al., 2006). Coordinates are in MNI space, and results are overlaid on the MNI template brain.

RESULTS

Behavioral Results

Behavioral data are presented in Figure 2. In all of our analyses of behavioral results, we performed univariate ANOVAs with Age Group as a between-subject variable and Condition (semantic, phonological) and Match Type (match, nonmatch) as within-subject variables. Because the perceptual task was qualitatively different from the other two conditions, we did not include it in our analyses of behavioral results. As several of our analyses of behavioral performance are dependent on the underlying RT distributions, we examined these to ensure that they were not markedly different as a function of Age Group, Condition, and Match Type.

RT

Analysis of the mean untransformed RT data for correct responses indicated a significant main effect of Age Group in which older adults responded more slowly than younger adults, $F(1, 30) = 6.81$, $p < .01$, and a main effect of Condition in which responses were faster in the semantic condition than in the phonological condition,

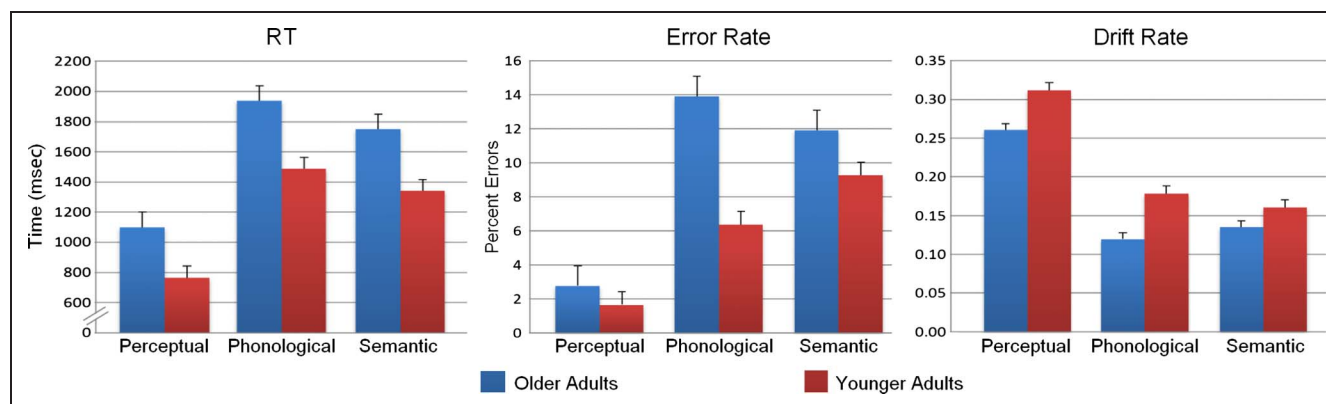


Figure 2. Behavioral results. Shown are group means for RT, error rate, and drift rate with standard error bars. Analyses of accuracy and drift rate revealed a significant interaction of Age Group and Condition. Drift rate analyses revealed that older adults were less accurate and efficient compared with younger adults during phonological judgments, but all participants performed similarly during semantic judgments.

$F(1, 30) = 46.96, p < .0001$. The interaction of Age Group \times Condition was not significant for untransformed RT, $F(1, 30) = 2.37, p < .13$. See also Figure 2. A significant main effect of Match, $F(1, 30) = 21.23, p < .0001$, was qualified by a significant Condition \times Match interaction, $F(1, 60) = 47.84, p < .0001$. Overall, match responses were faster than nonmatch responses, and this difference was significant in the phonological condition, $t(60) = 6.42, p < .01$, but not in the semantic condition.

Error Rate

An ANOVA yielded a significant main effect of Age Group, in which older adults made more errors than younger adults, $F(1, 30) = 13.45, p < .001$. Additionally, there was a significant Age Group \times Condition interaction, $F(1, 30) = 14.09, p < .001$, in which older adults made more errors than younger adults in the phonological condition, $t(62) = 22.21, p < .0001$, but not in the semantic condition. There was also a significant Match \times Condition interaction, $F(1, 30) = 31.19, p < .0001$. All participants made significantly more errors on nonmatch trials compared with match trials in the phonological condition, $t(62) = 8.02, p < .01$, whereas participants made significantly more errors on the match trials compared with the nonmatch trials in the semantic condition, $t(62) = 8.21, p < .005$. The Age Group \times Match interaction was also significant, $F(1, 30) = 4.24, p < .05$, with older adults making more errors on nonmatch trials and younger adults making more errors on match trials.

Retrieval Efficiency

We also examined behavioral performance using a diffusion model of RT that distinguishes the decision-related component of overall RT, termed drift rate (v), from the encoding and response-related components, termed nondecision time (T_{er} ; Wagenmakers, van der Maas, & Grasman, 2007; Voss, Rothermund, & Voss, 2004; Ratcliff, 1978). The diffusion model incorporates both RT and accuracy across participants in a combined model that yields estimates of the drift rate and nondecision time variables. This approach is similar in concept and result to analyses that modify raw RT by accuracy to account for overall efficiency (e.g., Horowitz & Wolfe, 2003; Townsend & Ashby, 1983).

Drift rate is assumed to vary across trials in response to the retrieval demands (and thus is modeled at the level of individual trials), whereas nondecision time is assumed to be constant across task conditions (and thus is modeled at the level of trial blocks). Increasing drift rate reflects increasing efficiency in retrieval of decision-related information, whereas increasing nondecision time reflects increasing time required for perceptual and motor processing. We conducted parameter estimation with the EZ diffusion model of Wagenmakers et al. (2007). The ANOVA

of drift rate yielded a significant main effect of Age Group, $F(1, 30) = 11.52, p < .01$, which was modified by a significant Age Group \times Condition interaction, $F(1, 30) = 13.28, p < .001$, such that older adults were less efficient compared with younger adults in the phonological condition, $t(62) = 25.234, p < .0001$, but not in the semantic condition. The drift rate analysis also yielded a significant Match \times Condition interaction, $F(1, 30) = 28.71, p < .0001$, because match responses were more efficient than nonmatch responses in the phonological condition, $t(62) = 10.56, p < .002$, but not in the semantic condition. This behavioral interaction effect of Match \times Condition for drift rates did not differ as a function of age group.

Nondecision Time

Because the match type and task condition variables were randomized across trials, only the age group difference in nondecision time can be estimated. The T_{er} values were significantly higher for older adults than for younger adults, $F(1, 30) = 22.79, p < .0001$, reflecting older adults' less efficient (slower and less accurate) perceptual encoding and motor responses.

fMRI Results

Activation to Individual Conditions

Collapsing across age groups revealed that both phonological and semantic conditions, relative to the perceptual control condition, elicited activation in established language-related regions that included bilateral IFG/insula, left pre- and post-central gyri, bilateral parahippocampal gyri, bilateral supramarginal gyri, and bilateral temporal cortex. These general comparisons also revealed activation in bilateral anterior cingulate, bilateral occipital cortex, and subcortical regions such as bilateral caudate. For the semantic $>$ control condition comparison, activation in the IFG extended farther laterally, parahippocampal activation was more extensive, and temporal activation included anterior middle temporal gyrus. For the phonological $>$ control condition comparison, this activation extended more medially into the insula. The perceptual condition $>$ baseline comparison elicited the smallest amount of activation, and this was seen in left precentral and postcentral gyri, bilateral supramarginal gyri, and bilateral occipital cortex. Activations to the individual conditions are shown in Figure 3.

Comparisons between Semantic and Phonological Conditions

For both age groups combined, the ANOVA yielded a main effect of Condition. The semantic condition elicited significantly greater activation than the phonological condition in left dorsal medial PFC, left middle frontal gyrus

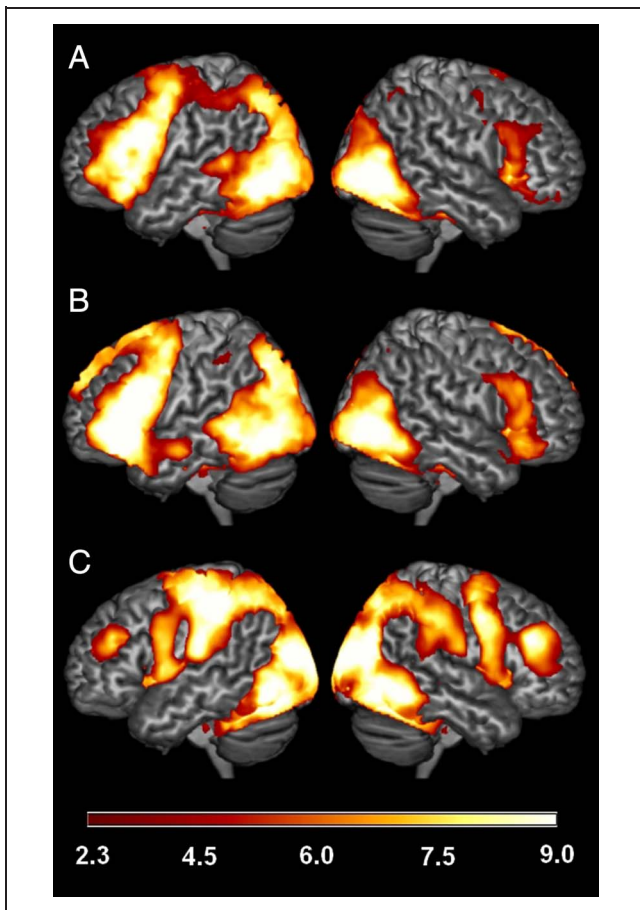
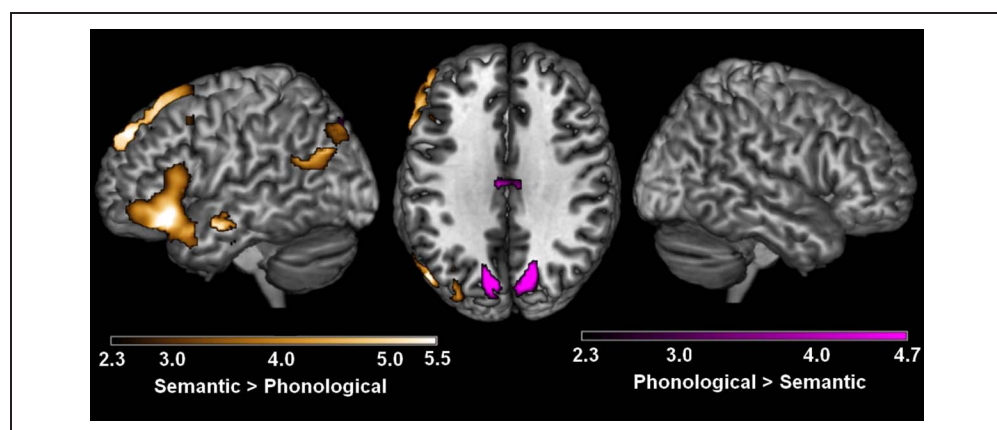


Figure 3. fMRI activations to individual conditions. Shown is an overview of the regions in which there was significant activation comparing (A) phonological trials > perceptual control condition, (B) semantic trials > perceptual control condition, and (C) the perceptual control condition > baseline, $p < .01$ corrected.

(MFG), left IFG which extended into left temporal pole, left middle temporal gyrus (MTG), and occipital cortex. The phonological condition elicited greater activation than the semantic condition in bilateral cingulate gyri and precuneus. These results are summarized and displayed in Figure 4 and Table 2.

Figure 4. Main effect of condition. Shown is an overview of the regions that comprise the main effect of condition. Regions in which the semantic condition elicited greater activation than the phonological condition are shown in tan and regions in which the phonological condition elicited greater activation than the semantic condition are shown in purple, $p < .01$ corrected.



Comparisons between Age Groups

The ANOVA yielded a main effect of Age, and the vast majority of these regions were areas where older adults elicited greater activation than younger adults. These regions are summarized in Figure 5 and Table 3. Comparisons between age groups showed that older adults elicited greater activation than younger adults in bilateral frontal pole, left OFC, left MFG, left dorsal medial PFC, bilateral pre-central gyri, bilateral post-central gyri, left insula, bilateral STG, bilateral MTG, bilateral superior parietal lobule and supramarginal gyri, right parahippocampal gyrus, bilateral precuneus, bilateral cerebellum, and bilateral subcortical regions. The occipital activation was extensive and included primary visual cortex, lateral occipital cortex, fusiform and lingual gyri, and portions of inferior temporal gyrus. Comparisons between age groups showed that the younger adults elicited greater activation than older adults in bilateral anterior cingulate and bilateral occipital cortex. In the left hemisphere, the occipital activation extended into left inferior temporal gyrus. The interaction of Condition and Age was not significant in the whole brain analysis.

Relations between Activation and Behavior: Main Effect of Condition

We were also interested in the relationship between functional activations and behavioral performance. To investigate this further, we conducted linear regressions in which Age Group, the parameter estimates of the fMRI activation in regions where there was a main effect of condition, and the interaction of Age Group and fMRI activation were independent variables (predictors), and drift rate was the outcome variable. For the phonological condition, functional activation was a significant predictor of phonological drift rate, $F(1, 30) = 2.72, p < .01$, as was the interaction between Age Group and fMRI activation, $F(1, 30) = 2.80, p < .01$. Moreover, the inclusion of these additional predictors reduced the age-related variance to the point where Age Group was no longer a significant

Table 2. Condition Effects

Region	Hemisphere	Voxels	Max Z		Peak (MNI)		
			Phonological	Semantic	x	y	z
<i>Semantic > Phonological</i>							
SFG	Left	1023	5.50	7.84	-8	48	40
MFG	Left	29	3.53	5.48	-40	16	50
IFG	Left	2728	8.10	10.30	-46	30	-16
MTG/STG	Left	166	1.99	4.27	-54	-2	-18
Occipital cortex	Left	625	6.00	8.87	-50	-68	28
Occipital cortex	Left	117	5.88	8.02	-32	-80	44
<i>Phonological > Semantic</i>							
ACC	Bilateral	65	3.07	1.64	6	-16	30
Precuneus, cuneus	Left	299	7.47	5.72	-10	-74	42
Precuneus, cuneus	Right	437	7.14	5.76	12	-70	40

predictor. Examination of the correlations revealed that the interaction between drift rate and activation to the phonological condition was driven by positive correlations for the younger adults (younger: $r = .76, p < .005$; older: $r = -.01, ns$).

In contrast to the results for the phonological condition, the regression that examined the relationship between functional activation and drift rate for the semantic condition showed that neither Age Group nor fMRI activation was a significant predictor of drift rate. However, the interaction between Age Group and fMRI activation was significant, $F(1, 30) = 2.40, p < .05$. Examination of the correlations revealed that the interaction between drift rate and activation to the semantic condition was driven by marginally significant positive correlations in the younger group (younger: $r = .44, p = .08$; older: $r = -.37, ns$). Older adults showed no overall correlation between activation and behavior for either condition. Statistical comparisons of the correlations between behavior and fMRI

activation across groups confirmed that the slopes were different for younger and older adults (phonological: $p < .01$, semantic condition: $p < .05$). Moreover, a comparison within younger adults confirmed that the correlation between drift rate and fMRI activation was stronger for the phonological condition ($p < .01$).

Finally, we investigated the degree to which individual differences in activation attenuated age-related variance in the drift rate measure (e.g., Salthouse, 1992). When Age Group was considered as the only predictor of phonological drift rate, Age Group accounted for 35.44% of the variance in this measure, $F(1, 30) = 16.47, p < .0005$. When fMRI activation was forced into the regression model before Age Group, the unique variance associated with Age Group was reduced to 9.39% and it was no longer a significant predictor of phonological drift rate. Its explanatory value was reduced by 75% (i.e., $[35.44 - 9.39]/35.44$), and the overall model R^2 increased from 35.44% to 58.42%. A similar but weaker pattern of results was also observed

Figure 5. Main effect of age. Shown is an overview of the regions that comprise the main effect of age. Regions in which younger adults elicited greater activation than older adults are shown in red and regions in which older adults elicited greater activation than younger adults are shown in blue, $p < .01$ corrected.

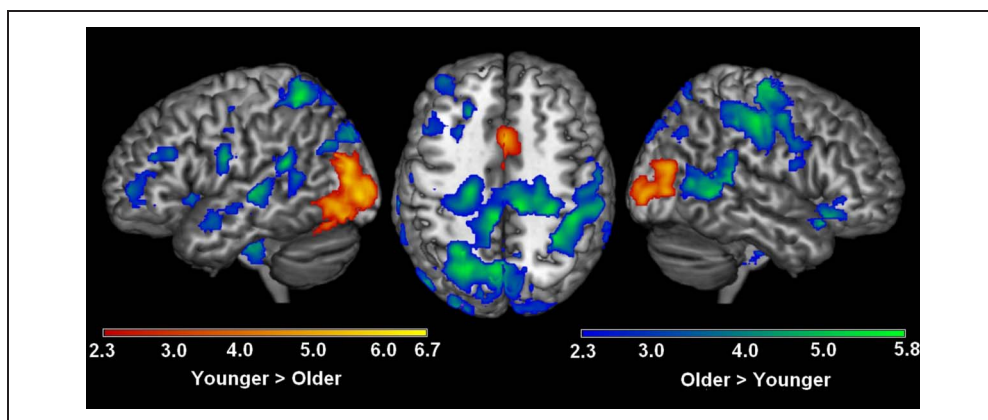


Table 3. Age Effects

Region	Hemisphere	Voxels	Max Z		Peak (MNI)		
			Younger	Older	x	y	z
<i>Older > Younger</i>							
Frontal pole	Left	1111	6.60	8.42	-22	38	20
Orbitofrontal cortex	Left	40	1.92	3.11	-22	28	-16
Orbitofrontal cortex	Left	66	2.33	3.44	-12	10	-14
Orbitofrontal cortex, TP	Right	243	3.47	5.63	48	22	-18
SFG	Left	46	1.54	2.76	-12	42	36
MFG	Left	198	8.25	10.79	-46	40	24
Precentral gyrus	Right	3315	8.17	10.98	10	-16	52
Postcentral gyrus	Right	2271	5.49	7.87	44	-22	46
Pre/post-central gyrus	Left	3726	8.70	10.45	-24	-2	26
Insula (anterior)	Left	639	7.57	9.08	-24	16	12
MTG/STG (anterior)	Left	178	1.88	2.93	-50	4	-18
MTG/STG (posterior)	Left	746	4.99	6.77	-50	-26	-2
MTG (temporo-occipital)	Right	913	9.34	11.60	46	-48	4
MTG (temporo-occipital)	Left	158	5.63	7.45	-60	-50	12
SPL	Left	1138	9.99	11.75	-30	-42	52
Supramarginal gyrus	Right	618	3.39	5.18	46	-44	8
Supramarginal gyrus	Left	471	5.44	6.86	-52	-44	20
Parahippocampal gyrus	Right	101	1.80	3.16	24	-18	24
Thalamus	Right	607	4.73	5.70	10	-20	-2
Thalamus	Left	549	5.60	6.48	-6	-22	-2
PCC	Bilateral	338	2.81	4.73	-10	-54	20
Precuneus	Right	867	6.00	8.36	10	-52	50
Precuneus	Left	1077	8.85	11.05	-6	-54	56
Precuneus	Right	444	6.13	7.40	12	-66	26
Precuneus	Left	186	4.41	5.68	-14	-64	18
Occipital cortex	Left	117	2.35	4.17	-48	-70	34
Occipital cortex	Left	193	8.45	10.43	-28	-88	38
Occipital cortex	Right	82	7.05	10.27	36	-66	42
Occipital pole	Right	204	7.99	9.97	8	-90	38
Cerebellum	Bilateral	1365	6.86	8.02	2	-60	-28
Brainstem	Bilateral	2554	4.80	6.32	-2	-30	-16
<i>Younger > Older</i>							
ACC	Bilateral	466	7.60	6.20	0	24	24
Caudate	Right	33	2.51	1.11	14	16	14
Occipital cortex	Left	4176	19.77	16.97	-28	-80	18
Occipital cortex	Right	1356	18.04	15.73	14	-92	-4

with semantic drift rate. When Age Group was considered as the only predictor of semantic drift rate, Age Group accounted for 12.97% of the variance in this measure, $F(1, 30) = 4.47, p < .05$. When fMRI activation was forced into the regression model before Age Group, the unique variance associated with Age Group was reduced to 8.88%, a reduction of 30%, and the overall model R^2 increased from 12.97% to 33.15% (Figure 6).

Relations between Activation and Behavior: Main Effect of Age

Similar to the analyses reported above, we investigated the relationship between activation and behavior for the main effect of Age. In regions where younger adults elicited greater activation than older adults, the interaction between Age Group and fMRI activation was a significant predictor of drift rate, $F(1, 30) = 2.26, p < .05$. In regions where older adults elicited greater activation than younger adults, Age Group was a significant predictor of

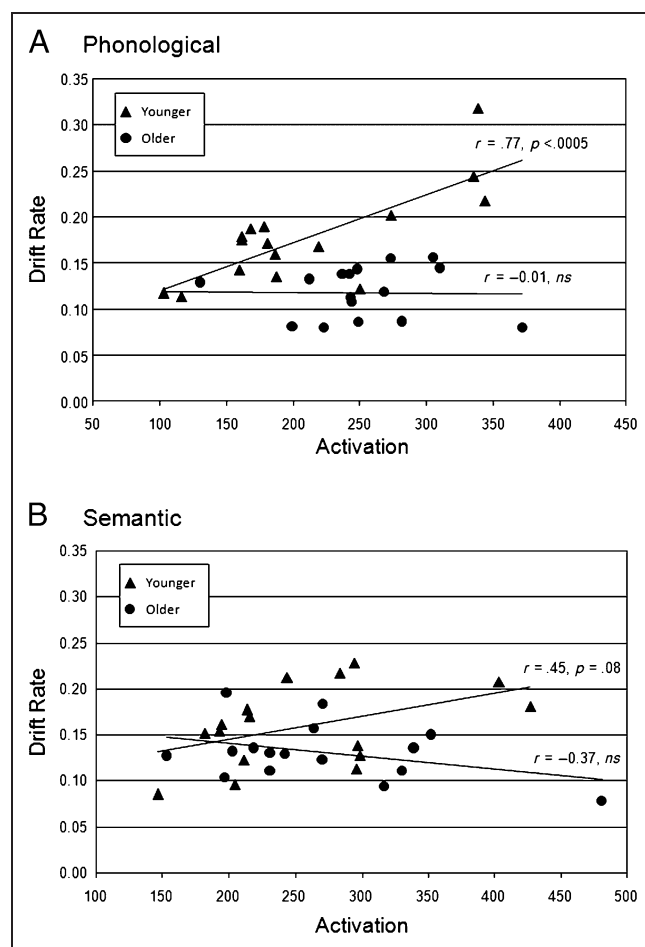


Figure 6. Scatterplots of the main effect of condition. Shown are scatterplots of the relationship between our behavioral measure of drift rate and estimates of the fMRI activation from the main effect of Condition. Significant correlations between behavior and fMRI activation were found for the younger group for both trial types. The correlation was strongest for the phonological condition.

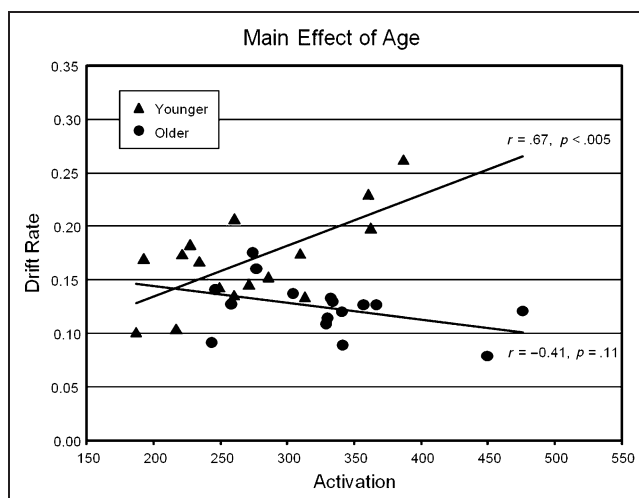


Figure 7. Scatterplot of the main effect of age by group. Shown are scatterplots of the relationship between our behavioral measure of drift rate and estimates of the fMRI activation from the main effect of age. As with the main effect of condition, significant correlations between behavior and fMRI activation were found for the younger group only.

drift rate, $F(1, 30) = -2.42, p < .05$, as was the interaction between Age Group and fMRI activation, $F(1, 30) = 3.56, p < .001$. fMRI activation was a marginally significant predictor of drift rate, $F(1, 30) = 1.86, p = .07$. Correlations between activation and behavior were similar for both regions in which younger adults elicited greater activation than older adults and vice versa and so we present a collapsed analysis here. The correlations indicated that the interaction between Age Group and fMRI was driven by positive correlations between functional activation and behavior for the younger adults (younger: $r = .67, p < .005$; older: $r = -0.41, p = .11$; Figure 7). Statistical comparisons of the correlations between behavior and fMRI activation across groups confirmed that the slopes were different for younger and older adults ($p < .005$). As with the main effect of Condition, older adults showed no overall correlation between activation and behavior in regions where there was a main effect of Age.

In regions where there was a main effect of Age Group, fMRI activation reduced age-related variance. When Age Group was considered as the only predictor of drift rate overall, Age Group accounted for 29.52% of the variance in this measure, $F(1, 30) = 12.57, p < .0001$. When fMRI activation was forced into the regression model before Age Group, the unique variance associated with Age Group was reduced to 11.24%, a reduction of 80%, and the overall model R^2 increased from 29.52% to 56.33%.

DISCUSSION

This study examined behavioral and neural aspects of phonological and semantic processes using a task in which older and younger adults made phonological, semantic,

and perceptual decisions about pictures. We hypothesized that the relation between these neural mechanisms and behavior would differ as a function of both age and retrieval condition. As predicted, the behavioral results demonstrated that older adults' semantic processes were well maintained, but phonological processes show a decline in accuracy and efficiency. This is consistent with previous studies reporting stability in semantic processes or age-related decline in phonological processes (see Burke & Shafto, 2008, for a review). This study, however, is the first to show this age dissociation in semantic and phonological decisions about the same pictures in a single experiment. We also found significant differences in the brain regions engaged by phonological and semantic decisions. Phonological processes engaged bilateral ACC and precuneus. The cingulate has a well-established role in general task control, and language control and monitoring, in particular during language production (Piai, Roelofs, Acheson, & Takashima, 2013; Abutalebi et al., 2008). Although our task did not involve overt production, participants had to retrieve the names of the pictures to successfully complete the phonological task. The precuneus' role in imagery and retrieval is well established (Kosslyn, 2003; Fletcher et al., 1995). Moreover, this region has been implicated in both auditory and visual forms of retrieval (Huijbers, Pennartz, Rubin, & Daselaar, 2011). Consistent with many previous studies, semantic processes elicited activation in traditional language regions within left frontal and temporal cortex.

Significant age differences were also found. Younger adults elicited greater activation in bilateral occipital and ventral brain regions that are important in the early stages of object identification. Younger adults also elicited greater activation in bilateral ACC and right caudate. Previous studies involving lexical decision have reported age-related differences in occipital and posterior temporal activation, though usually more left-lateralized (Whiting et al., 2003; Madden et al., 1996, 2002). Specifically, the Madden et al. (2002) PET study of lexical decision found that left occipital activation was higher for younger adults than for older adults and correlated with RT only for younger adults, which is a pattern similar to the present results. Madden et al. (2002) suggested that older adults may be maintaining a higher level of occipital activity in the baseline conditions, which would reduce the magnitude of the task minus baseline comparison for older adults.

In contrast, older adults elicited greater activation than younger adults in many regions throughout the brain. Although the interaction between Condition and Age Group was not significant in the whole-brain analysis of functional activation, we sought to better understand these age-related differences by looking at the relationship between brain activation and behavior in younger and older adults. A strong relationship between brain activation and behavior was found in younger, but not

older, adults. This was true in regions where there was a main effect of Condition and in regions where there was a main effect of Age. Older adults' behavior and brain activation failed to show significant relationships between one another, indicating that, although older adults may have increased neural recruitment, the additional activation is decoupled from behavioral performance.

Moreover, regressions that examined the relationship between performance, age, and fMRI activation for the phonological condition showed that including measures of functional activation reduced age-related variance in behavioral performance by 75% and improved the overall model R^2 from .35 to .58. Similar, but smaller, patterns were observed for the semantic condition. These results indicate that the pattern of brain activation provided additional explanatory value in understanding the patterns of behavioral performance.

Our results do not support compensatory neural models of aging in contrast with previous findings from episodic and working memory tasks, in which bilateral prefrontal recruitment was associated either with better performance among older adults (Cabeza, 2002; Reuter-Lorenz et al., 2000) or with maintained performance compared with younger adults (Wierenga et al., 2008). This difference in results may be related to the differences in cognitive domain (memory vs. language), although there is some support for compensatory accounts within the language domain (Geva et al., 2012; Peelle et al., 2010; Tyler et al., 2010). In contrast with the present results and in support of a compensation account, Geva et al. (2012) reported similar behavioral performance across age during a rhyme judgment and increased activation in right IFG for older adults. However, this age-related difference was significant only in an ROI analysis, not in a whole-brain analysis, suggesting that the effects were small. Moreover, task performance was at ceiling for the majority of participants which may have minimized age-related differences in behavior. This difference between Geva et al. and the current results may be especially relevant given that some models of age-related neurocognitive differences hypothesize that increased activation may be compensatory at lower levels of difficulty (Reuter-Lorenz & Cappell, 2008).

It is also possible that, when the neural networks are bilateral in younger adults as semantic and phonological processes tend to be, the magnitude or characterization of age-related differences are more subtle. In particular, both Peelle et al. (2010) and Tyler et al. (2010), whose results supported a compensatory account within the language domain, examined syntax, which is a highly left-lateralized function. These differences in hemispheric specialization and language process may in part account for the differences in results.

Our behavioral results are consistent with the transmission deficit theory, which predicts different aging effects for phonological and semantic processes. Transmission deficit theory postulates that aging weakens all connections,

thereby reducing the transmission of activation. Weaker connections, however, are less disruptive within the semantic system because of the greater number and redundancy among semantic connections compared with the phonological system (Burke, MacKay, & James, 2000; MacKay & Burke, 1990). Alternate theories of cognitive aging focus on general mechanisms such as inhibition (Lustig, Hasher, & Zacks, 2007; Hasher, Stoltzfus, Zacks, & Rypma, 1991; Hasher & Zacks, 1988) or speed (Salthouse, 1996; Lima, Hale, & Myerson, 1991; Cerella, 1985), which do not readily explain the asymmetry of age-related effects in phonological and semantic language processes.

There were several limitations to the current experiment. First, we did not find a significant Age \times Condition interaction in the whole-brain analysis of fMRI results. Although an interaction was present in behavioral performance and several of the analyses linked performance to fMRI activations in younger adults, it would have strengthened our results to find a significant interaction in the fMRI results. This is possibly because of our limited sample size. Although there was sufficient power to identify main effects in the fMRI analyses, it is possible that with additional participants we may have seen a significant interaction as well.

In conclusion, our results are consistent with an age-related decoupling between behavioral performance and neural activation. Behaviorally, older adults performed more poorly than younger adults on the phonological task, but not on the semantic task, demonstrating the predicted dissociation of aging effects. Neurally, older adults elicited more activation than younger adults throughout the brain, but a relation between behavior and activation was only found for younger adults. This combined pattern of increased functional activation with slower and more variable behavioral performance may represent a decline in efficiency and cause the link between activation and behavior to become weaker. This suggests that aging is characterized by a breakdown in the link between neural activation and behavior.

Acknowledgments

This project was funded by NIA grant R01 AG034138 (M. T. D.). D. J. M. was also supported by R01 AG039684. We thank Sarah Danehower for assistance with data analysis. We also thank the staff and scientists at the Brain Imaging and Analysis Center for their support of this project, especially the center director Allen W. Song.

Reprint requests should be sent to Michele T. Diaz, Brain Imaging and Analysis Center, Duke University, 2424 Erwin Road, Suite 501, Durham, NC 27705, or via e-mail: mtd3@duke.edu.

Note

1. Although the phonological question involved a letter cue, correct responses required phonological retrieval of the object name because orthographic retrieval is mediated by phonology (e.g., Bonin, Peereman, & Fayol, 2001).

REFERENCES

- Abutalebi, J., Annoni, J. M., Zimine, I., Pegna, A. J., Seghier, M. L., Lee-Jahnke, H., et al. (2008). Language control and lexical competition in bilinguals: An event-related fMRI study. *Cerebral Cortex*, *18*, 1496–1505.
- Alwin, D. F., & McCammon, R. J. (2001). Aging, cohorts, and verbal ability. *Journals of Gerontology, Series B, Psychological Sciences and Social Sciences*, *56*, S151–S161.
- Balota, D. A., Yap, M. J., Cortese, M. J., Hutchison, K. I., Kessler, B., Loftis, B., et al. (2007). The English Lexicon Project. *Behavior Research Methods*, *39*, 445–459.
- Beckmann, C. F., Jenkinson, M., & Smith, S. M. (2003). General multilevel linear modeling for group analysis in fMRI. *Neuroimage*, *20*, 1052–1063.
- Bonin, P., Peereman, R., & Fayol, M. (2001). Do phonological codes constrain the selection of orthographic codes in written picture naming? *Journal of Memory & Language*, *45*, 688–720.
- Bowles, N. L. (1989). Age and semantic inhibition in word retrieval. *Journal of Gerontology*, *44*, P88–P90.
- Bowles, N. L., Williams, D., & Poon, L. W. (1983). On the use of word association norms in aging research. *Experimental Aging Research*, *9*, 175–177.
- Burke, D. M., & Graham, E. R. (2012). The neural basis for aging effects on language. In M. E. Faust (Ed.), *The handbook of the neuropsychology of language* (pp. 778–800). Oxford, UK: Blackwell Publishing Ltd.
- Burke, D. M., MacKay, D. G., & James, L. E. (2000). Theoretical approaches to language and aging. In T. J. Perfect & E. A. Maylor (Eds.), *Models of cognitive aging* (pp. 204–237). New York: Oxford University Press.
- Burke, D. M., Mackay, D. G., Worthley, J. S., & Wade, E. (1991). On the tip of the tongue: What causes word finding failures in young and older adults? *Journal of Memory and Language*, *30*, 542–579.
- Burke, D. M., & Peters, L. (1986). Word associations in old age: Evidence for consistency in semantic encoding during adulthood. *Psychology and Aging*, *1*, 283–292.
- Burke, D. M., Peters, L., & Harrold, R. M. (1987). Word association norms for young and older adults. *Social & Behavioral Science Documents*, *17*, 1–78.
- Burke, D. M., & Shafto, M. A. (2008). Language and aging. In F. I. M. Craik & T. A. Salthouse (Eds.), *The handbook of aging and cognition* (3rd ed., pp. 373–443). New York: Psychology Press.
- Cabeza, R. (2002). Hemispheric asymmetry reduction in older adults: The HAROLD model. *Psychology and Aging*, *17*, 85–100.
- Cabeza, R., Anderson, N. D., Locantore, J. K., & McIntosh, A. R. (2002). Aging gracefully: Compensatory brain activity in high performing older adults. *Neuroimage*, *17*, 1394–1402.
- Cerella, J. (1985). Information processing rates in the elderly. *Psychological Bulletin*, *98*, 67–83.
- Dale, A. M. (1999). Optimal experimental design for event-related fMRI. *Human Brain Mapping*, *8*, 109–114.
- Daselaar, S. M., Veltman, D. J., Rombouts, S. A. R. B., Raaijmakers, J. G. W., & Jonker, C. (2003). Deep processing activates the medial temporal lobe in young but not in old adults. *Neurobiology of Aging*, *24*, 1005–1011.
- Desikan, R. S., Segonne, F., Fischl, B., Quinn, B. T., Dickerson, B. C., Blacker, D., et al. (2006). An automated labeling system for subdividing the human cerebral cortex on MRI scans into gyral based regions of interest. *Neuroimage*, *31*, 968–980.
- Fjell, A. M., & Walhovd, K. B. (2010). Structural brain changes in aging: Courses, causes and cognitive consequences. *Reviews in the Neurosciences*, *21*, 187–221.

- Fletcher, P. C., Frith, C. D., Baker, S. C., Shallice, T., Frackowiak, R. S., & Dolan, R. J. (1995). The mind's eye—Precuneus activation in memory-related imagery. *Neuroimage*, *2*, 195–200.
- Friedman, L., & Glover, G. H. (2006). Report on a multicenter fMRI quality assurance protocol. *Journal of Magnetic Resonance Imaging*, *23*, 827–839.
- Geva, S., Jones, P. S., Crinion, J. T., Price, C. J., Baron, J. C., & Warburton, E. A. (2012). The effect of aging on the neural correlates of phonological word retrieval. *Journal of Cognitive Neuroscience*, *24*, 2135–2146.
- Glover, G. H., Mueller, B., Van Erp, T., Liu, T. T., Greve, D., Voyvodic, J., et al. (2012). Function biomedical informatics research network recommendations for prospective multicenter functional neuroimaging studies. *Journal of Magnetic Resonance Imaging*, *36*, 39–54.
- Greve, D. N., & Fischl, B. (2009). Accurate and robust brain image alignment using boundary-based registration. *Neuroimage*, *48*, 63–72.
- Hasher, L., Stoltzfus, E. R., Zacks, R. T., & Rypma, B. (1991). Age and inhibition. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *17*, 163–169.
- Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 22, pp. 193–225). San Diego, CA: Academic Press.
- Hayasaka, S., & Nichols, T. E. (2003). Validating cluster size inference: Random field and permutation methods. *Neuroimage*, *20*, 2343–2356.
- Horowitz, T. S., & Wolfe, J. M. (2003). Memory for rejected distractors in visual search? *Visual Cognition*, *10*, 257–298.
- Howard, D. V. (1980). Category norms: A comparison of the Battig and Montague (1969) norms with the responses of adults between the ages of 20 and 80. *Journal of Gerontology*, *35*, 225–231.
- Huijbers, W., Pennartz, C. M., Rubin, D. C., & Daselaar, S. M. (2011). Imagery and retrieval of auditory and visual information: Neural correlates of successful and unsuccessful performance. *Neuropsychologia*, *49*, 1730–1740.
- James, L. E., & Burke, D. M. (2000). Phonological priming effects on word retrieval and tip-of-the-tongue experiences in young and older adults. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *26*, 1378–1391.
- Jenkinson, M., Bannister, P. R., Brady, J. M., & Smith, S. M. (2002). Improved optimisation for the robust and accurate linear registration and motion correction of brain images. *Neuroimage*, *17*, 825–841.
- Jenkinson, M., & Smith, S. M. (2001). A global optimisation method for robust affine registration of brain images. *Medical Image Analysis*, *5*, 143–156.
- Johnson, S. C., Saykin, A. J., Flashman, L. A., McAllister, T. W., O'Jile, J. R., Sparling, M. B., et al. (2001). Similarities and differences in semantic and phonological processing with age: Patterns of functional MRI activation. *Aging, Neuropsychology, & Cognition*, *8*, 307–320.
- Kosslyn, S. M. (2003). Understanding the mind's eye...and nose. *Nature Neuroscience*, *6*, 1124–1125.
- Kriegeskorte, N., Simmons, W. K., Bellgowan, P. S., & Baker, C. I. (2009). Circular analysis in systems neuroscience: The dangers of double dipping. *Nature Neuroscience*, *12*, 535–540.
- Light, L. L., Owens, S. A., Mahoney, P. G., & LaVoie, D. (1993). Comprehension of metaphors by young and older adults. In J. Cerella, W. Hoyer, J. Rybash, & M. L. Commons (Eds.), *Adult information processing: Limits on loss* (pp. 459–488). New York: Academic Press.
- Lima, S. D., Hale, S., & Myerson, J. (1991). How general is general slowing? Evidence from the lexical domain. *Psychology and Aging*, *6*, 416–425.
- Lindenberger, U., & Baltes, P. B. (1997). Intellectual functioning in old and very old age: Cross-sectional results from the Berlin Aging Study. *Psychology and Aging*, *12*, 410–432.
- Little, D. M., Prentice, K. J., & Wingfield, A. (2004). Adult age differences in judgments of semantic fit. *Applied Psycholinguistics*, *25*, 135–143.
- Logan, J. M., Sanders, A. L., Snyder, A. Z., Morris, J. C., & Buckner, R. L. (2002). Under-recruitment and nonselective recruitment: Dissociable neural mechanisms associated with aging. *Neuron*, *33*, 827–840.
- Loibl, M., Beutling, W., Kaza, E., & Lotze, M. (2011). Non-effective increase of fMRI-activation for motor performance in elder individuals. *Behavioural Brain Research*, *223*, 280–286.
- Lustig, C., Hasher, L., & Zacks, R. T. (2007). Inhibitory deficit theory: Recent developments in a “new view”. In D. S. Gorfein & C. M. MacLeod (Eds.), *The place of inhibition in cognition* (pp. 145–162). Washington, DC: American Psychological Association.
- MacKay, D. G., & Burke, D. M. (1990). Cognition and aging: New learning and the use of old connections. In T. M. Hess (Ed.), *Aging and cognition: Knowledge organization and utilization* (pp. 213–263). Amsterdam: North Holland.
- MacKay, D. G., & James, L. E. (2004). Sequencing, speech production, and selective effects of aging on phonological and morphological speech errors. *Psychology and Aging*, *19*, 93–107.
- Madden, D. J., Bennett, I. J., Burzynska, A., Potter, G. G., Chen, N. K., & Song, A. W. (2012). Diffusion tensor imaging of cerebral white matter integrity in cognitive aging. *Biochimica et Biophysica Acta*, *1822*, 386–400.
- Madden, D. J., Langley, L. K., Denny, L. L., Turkington, T. G., Provenzale, J. M., Hawk, T. C., et al. (2002). Adult age differences in visual word identification: Functional neuroanatomy by positron emission tomography. *Brain and Cognition*, *49*, 297–321.
- Madden, D. J., Pierce, T. W., & Allen, P. A. (1993). Age-related slowing and the time course of semantic priming in visual word identification. *Psychology and Aging*, *8*, 490–507.
- Madden, D. J., Turkington, T. G., Coleman, R. E., Provenzale, J. M., DeGrado, T. R., & Hoffman, J. M. (1996). Adult age differences in regional cerebral blood flow during visual word identification: Evidence from H215O PET. *Neuroimage*, *3*, 127–142.
- Meinzer, M., Fleisch, T., Wilser, L., Eutiz, C., Rockstroh, B., Conway, T., et al. (2009). Neural signatures of semantic and phonemic fluency in young and old adults. *Journal of Cognitive Neuroscience*, *21*, 2007–2018.
- Oldfield, R. C., & Wingfield, A. (1965). Response latencies in naming objects. *Quarterly Journal of Experimental Psychology*, *17*, 273–281.
- Peelle, J. E., Troiani, V., Wingfield, A., & Grossman, M. (2010). Neural processing during older adults' comprehension of spoken sentences: Age differences in resource allocation and connectivity. *Cerebral Cortex*, *20*, 773–782.
- Piai, V., Roelofs, A., Acheson, D. J., & Takashima, A. (2013). Attention for speaking: Domain-general control from the anterior cingulate cortex in spoken word production. *Frontiers in Human Neuroscience*, *7*, 832.
- Ratcliff, R. (1978). A theory of memory retrieval. *Psychological Review*, *85*, 59–108.
- Raz, N. (2005). The aging brain observed in vivo: Differential changes and their modifiers. In R. Cabeza, L. Nyberg, & D. Park (Eds.), *Cognitive neuroscience of aging: Linking cognitive and cerebral aging* (pp. 19–57). Oxford: Oxford University Press.
- Reuter-Lorenz, P., Jonides, J., Smith, E. S., Hartley, A., Miller, A., Marschuetz, C., et al. (2000). Age differences in the frontal

- lateralization of verbal and spatial working memory revealed by PET. *Journal of Cognitive Neuroscience*, *12*, 174–187.
- Reuter-Lorenz, P. A., & Cappell, K. A. (2008). Neurocognitive aging and the compensation hypothesis. *Current Directions in Psychological Science*, *17*, 177–182.
- Riecker, A., Gröschel, K., Ackermann, H., Steinbrink, C., Witte, O., & Kastrup, A. (2006). Functional significance of age-related differences in motor activation patterns. *Neuroimage*, *32*, 1345–1354.
- Salat, D. H. (2011). The declining infrastructure of the aging brain. *Brain Connectivity*, *1*, 279–293.
- Salthouse, T. A. (1992). *Mechanisms of age-cognition relations in adulthood*. Hillsdale, NJ: Erlbaum.
- Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review*, *103*, 403–428.
- Schaie, K. W. (2005). *Developmental influences on adult intellectual development: The Seattle Longitudinal Study*. New York: Oxford University Press.
- Shafto, M. A., Randall, B., Stamatakis, E. A., Wright, P., & Tyler, L. K. (2012). Age-related neural reorganization during spoken word recognition: The interaction of form and meaning. *Journal of Cognitive Neuroscience*, *24*, 1434–1446.
- Shafto, M. A., Stamatakis, E. A., Tam, P. P., & Tyler, L. K. (2010). Word retrieval failures in old age: The relationship between structure and function. *Journal of Cognitive Neuroscience*, *22*, 1530–1540.
- Singer, T., Verhaeghen, P., Ghisletta, P., Lindenberger, U., & Baltes, P. B. (2003). The fate of cognition in very old age: Six-year longitudinal findings in the Berlin Aging Study (BASE). *Psychology and Aging*, *18*, 318–331.
- Smith, S. M. (2002). Fast robust automated brain extraction. *Human Brain Mapping*, *3*, 143–155.
- Smith, S. M., Jenkinson, M., Woolrich, M. W., Beckman, C. F., Behrens, T. E. J., Johansen-Berg, H., et al. (2004). Advances in functional and structural MR image analysis and implementation as FSL. *Neuroimage*, *23*, 208–219.
- Stebbins, G. T., Carrillo, M. C., Dorfman, J., Dirksen, C., Desmond, J. E., Turner, D. A., et al. (2002). Aging effects on memory encoding in the frontal lobes. *Psychology and Aging*, *17*, 44–55.
- Taylor, J. K., & Burke, D. M. (2000). *Slips of the tongue: An examination of language production in old age*. Paper presented at the Cognitive Aging Conference, Atlanta, GA.
- Townsend, J. T., & Ashby, F. G. (1983). *The stochastic modeling of elementary psychological processes*. Cambridge, UK: Cambridge University Press.
- Tyler, L. K., Shafto, M. A., Randall, B., Wright, P., Marslen-Wilson, W. D., & Stamatakis, E. A. (2010). Preserving syntactic processing across the adult life span: The modulation of the frontotemporal language system in the context of age-related atrophy. *Cerebral Cortex*, *20*, 352–364.
- Verhaeghen, P. (2003). Aging and vocabulary score: A meta-analysis. *Psychology and Aging*, *18*, 332–339.
- Voss, A., Rothermund, K., & Voss, J. (2004). Interpreting the parameters of the diffusion model: An empirical validation. *Memory & Cognition*, *32*, 1206–1220.
- Vousden, J. I., & Maylor, E. A. (2006). Speech errors across the lifespan. *Language and Cognitive Processes*, *21*, 48–77.
- Voyvodic, J. T. (1999). Real-time fMRI paradigm control, physiology, and behavior combined with near real-time statistical analysis. *Neuroimage*, *10*, 91–106.
- Wagenmakers, E.-J., van der Maas, H. L. J., & Grasman, R. (2007). An EZ-diffusion model for response time and accuracy. *Psychonomic Bulletin & Review*, *14*, 3–22.
- White, K. K., & Abrams, L. (2002). Does priming specific syllables during tip-of-the-tongue states facilitate word retrieval in older adults? *Psychology and Aging*, *17*, 226–235.
- Whiting, W. L., Madden, D. J., Langley, L. K., Denny, L. L., Turkington, T. G., Provenzale, J. M., et al. (2003). Lexical and sublexical components of age-related changes in neural activation during visual word identification. *Journal of Cognitive Neuroscience*, *15*, 475–487.
- Wierenga, C. E., Benjamin, M., Gopinath, K., Perlstein, W. M., Leonard, C. M., Gonzalez Rothi, L. J., et al. (2008). Age-related changes in word retrieval: Role of bilateral frontal and subcortical networks. *Neurobiology of Aging*, *29*, 436–451.
- Woolrich, M. W., Behrens, T. E. J., Beckman, C. F., Jenkinson, M., & Smith, S. M. (2004). Multi-level linear modelling for fMRI group analysis using Bayesian inference. *Neuroimage*, *21*, 1732–1747.
- Woolrich, M. W., Jbabdi, S., Patenaude, B., Chappell, M., Makni, S., Behrens, T. E. J., et al. (2009). Bayesian analysis of neuroimaging data in FSL. *Neuroimage*, *45*, S173–S186.
- Woolrich, M. W., Ripley, B. D., Brady, J. M., & Smith, S. M. (2001). Temporal autocorrelation in univariate linear modelling of fMRI data. *Neuroimage*, *6*, 1370–1386.