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INFLUENCE OF ENCODING DIFFICULTY, WORD FREQUENCY, AND PHONOLOGICAL REGULARITY ON AGE DIFFERENCES IN WORD NAMING

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It is presently unclear as to why older adults take longer than younger adults to recognize visually presented words. To examine this issue in more detail, the authors conducted two word-naming studies (Experiment 1: 20 older adults and 20 younger adults; Experiment 2: 60 older adults and 60 younger adults) to determine the relative effects of orthographic encoding (case type), lexical access (word frequency), and phonological regularity (regular vs. irregular phonology). The hypothesis was that older adults attempt to compensate for sensory and motor slowing by using progressively larger perceptual units (holistic encoding). However, if forced to use smaller perceptual units (e.g., by using mixed-case presentation), it was predicted that older adults would be particularly challenged. Older adults did show larger case-mixing effects than younger adults (suggesting that older adults' performances were especially poor when they were forced to use smaller perceptual units), but there were no age differences in word frequency or phonological regularity even though both age groups showed main effects for these variables. These results suggest that lexical access skill remains stable in the addressed (orthographic/semantic) and assembled (phonological) routes over the life span, but that older adults slow down in recognizing words because it takes them longer to normalize (perceptually "clean up") noisier sensory information.

A consistent result in cognitive aging research is that older adults take longer to recognize words than do younger adults (Allen, Madden, & Slane, 1995; Balota & Ferraro, 1993, 1996). By recognize, we mean either discriminating between words or nonwords (a lexical decision task) or naming words (a pronunciation task). Because of the centrality of visual word recognition to reading, it is important to know why this age-related slowing occurs. It could be due to general slowing across multiple processing stages (e.g., Cerella, 1985; Madden, 1992; Salthouse, 1996), or more specific, age-related deficits at orthographic encoding (Allen, Madden, & Crozier, 1991; Allen, Madden, Weber, & Groth, 1993), lexical access (Balota & Ferraro, 1993, 1996), or phonological processing (MacKay & James, 2004). In order to more precisely examine how these variables affect age differences in visual word recognition, we for the first time examined age differences in perceptual orthographic encoding (case mixing), lexical access (word frequency), and phonological regularity (a measure of grapheme-to-phoneme correspondence, or GPC, processing: exception words vs. regular-inconsistent words vs. regular controls) on a word-naming task. This allowed us to take advantage of the joint method of agreement and difference to isolate the locus/loci of the age effect(s).

Our working hypothesis was that older adults attempt to compensate for greater sensory slowing (relative to younger adults; see Lindenberger & Baltes, 1994) by using larger perceptual units of analysis. In the present hybrid model of visual word recognition (Allen, Wallace, & Weber, 1995), once selective attention is applied to a stimulus, parallel independent holistic and analytic streams involved in a stochastic horse race are formed in a bottom-up signal-processing manner. Because the amount of light reaching a typical 60-year-old's retinas is one-third that of the amount of light reaching a typical 20-year-old's retina (Pitts, 1982), older adults probably need to carry out more normalization processing (Allen, Wallace, & Weber, 1995). By normalization, we refer to spatial-frequency filtering that uses signal processing of lower-spatial-frequency information (for global, holistic objects—in the case of words, multiletter units up to whole words) and higher-spatial-frequency information (for analytic "pieces" of objects—in the case of words, component letters) (Allen, Smith, Lien, Kaut, & Canfield, 2009). Note that the advantage of using the global route is that no attentional binding processing is needed (see Kveraga, Boshyan, & Bar, 2007), whereas analytic letter-by-letter information must be attentionally bound into words (referred to as a superposition process; Allen, Wallace, et al., 1995). A central assumption of the present work is that in spite of older adults having weaker sensory information due to poorer visual acuity (thereby requiring more normalization processing on the part of older adults), it is still advantageous for older adults to recognize words as holistic perceptual objects rather than analytically encoding and binding/superposing words in a piecemeal manner. Mixing case is thought to disrupt the formation of larger perceptual units (Allen et al., 1993, 1995), so our working hypothesis leads to the prediction that older adults show relatively larger case-mixing effects than younger adults, but that there should be no appreciable age effects for word frequency or phonological regularity.

Most current models of visual word recognition also include two different processing paths: addressed and assembled routes (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001). An addressed path uses graphemes (or the basic letter units of English, and/or multiletter units) to access the mental lexicon. Alternatively, an assembled path uses GPC rules and/or multiletter units such as onsets (the initial consonant or vowel, or blend, at the beginning of a word) and rimes (the rest of the word) to pronounce but not to identify words through lexical access. Because the assembled route can interfere with the addressed route that might affect word frequency effects, we included manipulations that have been found to cause such interference to see if they would interact with age.

To examine how increased adult age affects addressed and assembled processing, we used a naming task (which emphasizes phonological processing so that individuals can name words) in which we measured the pronunciation time for visually presented words. We used the Seidenberg, Waters, Barnes, and Tanenhaus (1984) (Experiment 1) and the Taraban and McClelland (1987) (Experiment 2) word stimuli because these stimulus sets include regularity and consistency indices of processing that are thought to affect the speed with which a word can be named by the addressed path. We also included case type and word frequency because case type is assumed to affect orthographic encoding difficulty (Allen et al., 1993; Allen et al., 2009; Coltheart & Freeman, 1974) and word frequency is assumed to measure lexical access speed and sensitivity (Allen, Smith, Lien, Grabbe, & Murphy, 2005). Word frequency effects in visual word recognition are thought to have multiple loci—both perceptual activation/lexical access (Allen, Smith, et al., 2005; Monsell, Doyle, & Haggard, 1989) and response decision (e.g., Balota & Chumbley, 1984)—although there is accumulating evidence that a significant portion of this frequency effect is the result of lexical access (Allen et al., 2005).

A Model of Visual Word Recognition

The present stochastic, hybrid model is based on a similar model developed by Allen et al. (1995, 2009) and includes two types of addressed routes (holistic and analytic) and two types of assembled routes (holistic and analytic; see Figure 1). The model assumes that all of these codes are formed in parallel and independently using spatial-frequency filtering. However, the increased efficiency of processing a word holistically (as a multiletter unit) and thereby bypassing attentional binding compared to analytically (as a series of individual letter-level codes) allows individuals to process words more efficiently as long as stimuli are presented in a form for which holistic word recognition is possible—such as when a familiar spatial-frequency pattern of whole words is present (e.g., lowercase presentation; Allen et al., 1995, 2009; Graham, 1981). When words are presented in mixed case, they probably need to be encoded by component letters because the global pattern will not be familiar. Another very real possibility, though, is that even when a word stimulus is presented in a familiar spatial-frequency form, older adults' poorer retinal resolution capability (particularly for lower-spatial-frequency information; see Gilmore, Groth, & Thomas, 1995) will

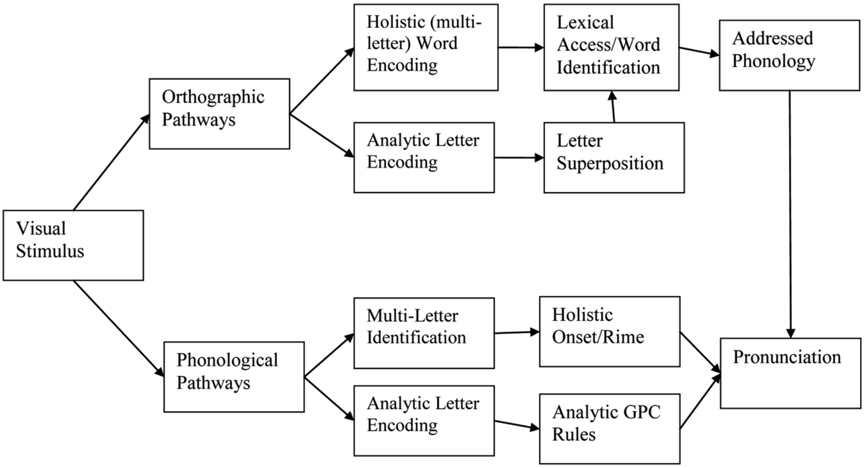

Figure 1. The holistically biased hybrid model.

not allow them to successfully normalize global words on some attempts—thereby forcing older adults to use slower analytic orthographic encoding that requires an additional binding/superposition process. The rationale behind the present case-mixing manipulation is that it provides a plausible scenario in which both age groups almost certainly must carry out the more complex attentional binding process to recognize a word. Although individuals rarely encounter mixed-case text in real-world reading, we are using this as a proxy for what older adults would encounter if they could not normalize a global perceptual object and were forced to recognize the object through separate smaller pieces and then needed to superpose these subunits into a complete word.

This sort of multiroute model proposed in the present study is an embellished dual-route model (e.g., Forster & Chambers, 1973; Herdman, Chernicki, & Norris, 1999), except that the present hybrid model has a holistic addressed pathway that is independent of the multiletter assembled input channel of Herdman et al. (1999; also see Norris, 1994). The addressed routes are thought to be formed from spatial-frequency patterns of the analytic and holistic input channels, whereas the assembled input channels form phonological codes from analytic codes (or GPC rules) or holistic multiletter units being converted to sounds (onsets and rimes). This sort of parallel multiroute model can account for case-mixing effects and for regularity effects. By regularity effects, we are referring to the finding that words whose pronunciations are different from most of their orthographic neighbors (e.g., “have,” we will refer to this as an exception word; see Taraban & McClelland, 1987) tend to take longer to pronounce than regular controls (e.g., “beam”) that have regular pronunciations and have orthographic neighbors that are also pronounced regularly (Herdman et al., 1999). Finally, a word can be consistent with most of its orthographic neighbors, but have a small subset (or even one) of orthographic neighbor(s) that are inconsistent (e.g., “cave,” “gave,” “pave,” “save” are classified as “regular-inconsistent” words because “have” is an orthographic neighbor that is irregular even though most orthographic neighbors are regular). The literature is quite varied in this last category of words because some studies have found a regular-inconsistent disadvantage for word recognition (e.g., Seidenberg et al., 1984), but others have not (Taraban & McClelland, 1987, Experiments 1a and 1b). In the present study, we are primarily interested in phonological regularity (exception words vs. regular controls) rather than regular–inconsistent words.

Dual-route models hypothesize that both lexical (addressed, in the multiroute model, either analytic or holistic, or both) and rule-based assembled (GPC) routes can be used to process words with regular pronunciations, but that just the lexical route(s) can be used to process exception words (Herdman et al., 1999). Given that exception words result in “differential outputs” for lexical and assembled routes, this model predicts that performance will be poorer for such words—particularly for lower-frequency words. This is because it is assumed that the lexical route tends to win the processing race for higher-frequency words, but that both the lexical and assembled route (or routes—depending on whether there is a single grapheme-based system or both grapheme and multiletter units systems, such as onsets and rimes) have similar output times for lower-frequency words, resulting in greater interference. Given that the assembled route cannot lead to pronunciation for exception words and that lower-frequency words result in similar completion times for both assembled and lexical routes, but the lexical route must be used for pronunciation, dual-route models predict a Regularity (exception vs. regular control) × Word Frequency (high vs. low) interaction in which exception words take longer to pronounce (than regular-inconsistent and regular-control words) for lower-frequency words, but not for higher-frequency words.

An alternative view of visual word recognition (relative the dual-route models) is that letter-level (analytic) information is formed through the use of feature analysis. This letter-level information is then used to form word-level (holistic) codes and these word-level codes are then used to process phonological-level codes (e.g., McClelland & Rumelhart, 1981; Taraban & McClelland, 1987; also see Norris, 1994, for a variation of this model). We will refer to this as the interactive activation model (McClelland & Rumelhart, 1981). Although there is some evidence that the interactive activation model cannot readily account for the combination of letter identification task and lexical decision task data in which word frequency is manipulated (e.g., Allen & Emerson, 1991; Jordan, 1995; Jordan & Bevan, 1996; Jordan, Thomas, Patching, & Scott-Brown, 2003), this interactive activation model of visual word recognition does make predictions about naming performance that run somewhat counter to those of dual- (or multi-) route models, so we will include regular-inconsistent words as well as exception and regular control words in the present experiments.

In particular, interactive activation models of visual word recognition predict more comprehensive "conspiracy" effects for word pronunciation than do multiroute models. That is, for interactive activation models, the pronunciation of a given word or nonword is predicted to be affected by word "neighbors" that are similar orthographically to the given word or nonword (Taraban & McClelland, 1987). Thus, interactive activation models predict that not only exception words like "have" will take longer to pronounce than phonologically regular words with no orthographic neighbors that are phonologically irregular (regular controls, e.g., "beam"), but that phonologically regular words with at least one orthographic neighbor that is phonologically irregular (regular-inconsistent, e.g., "save"—because "have" is an orthographic neighbor) will also take longer to pronounce than normal controls.

Age Differences and Basic Units of Analysis in Visual Word Recognition

As noted previously, we assume that mixing case on a visual word recognition task affects which input channel can output a code. One could argue that larger case-mixing effects for older adults could just as well be accounted for by assuming that older adults are more disrupted than younger adults at an entirely analytic feature-extraction stage of processing. However, results from letter identification and lexical decision studies that varied word frequency are inconsistent with this interpretation. For example, Allen and Madden (1989) and Allen et al. (1991) found that younger adults showed a non-monotonic effect for word frequency on a letter identification task (i.e., letters in medium-high-frequency words took longer to identify than letters in high-frequency or low-frequency words), but older adults showed a word frequency advantage (letters were identified in high-frequency words faster than in lower-frequency words). Allen et al. (1991) also demonstrated that both age groups showed this same word frequency advantage on a lexical decision task. These results suggested that older adults were actually segmenting words into letter-level codes (i.e., breaking a holistic code into analytic codes in working memory). Alternatively, younger adults appeared to be significantly more efficient at forming parallel analytic codes—albeit at a typically slower rate than holistic codes.

There are two variables, case mixing and word frequency, that are particularly relevant to the present issue of whether age differences in visual word recognition latency are due to orthographic encoding or semantic memory retrieval/lexical access, respectively. We assume that word frequency effects measure the speed of lexical access/semantic memory retrieval for a presented word on a lexical decision task (e.g., Allen et al., 2005; Andrews & Heathcote, 2001). In our earlier lexical decision research, we found either equivalent word frequency effects across age (Allen et al., 1991, 1993; Allen, Lien et al., 2002; Lien et al., 2006) or smaller word frequency effects for older adults (Allen, Murphy, Kaufman, Groth, & Begovic, 2004). Balota, Cortese, Sargent-Marshall, Spieler, and Yap (2004) also found comparable word frequency effects for a lexical decision task (for combined objective and subjective word frequency measures, although older adults showed larger word frequency effects for just subjective word frequency measures). On the other hand, Balota and Ferraro (1996) found slightly larger word frequency effects for older adults than for younger adults. What the preponderance of these lexical decision results suggests is that healthy older adults probably exhibit at least as efficient of lexical access as do younger adults.

Because word frequency effects are thought to in large part measure lexical access/semantic retrieval (e.g., Allen et al., 2005; Andrews & Heathcote, 2001; Monsell et al., 1989), we believe that there is considerable empirical support to assume that there should be no appreciable age differences in this type of information processing. This is because although there are substantial age differences in contextual/episodic memory, there is little evidence of appreciable age deficits in semantic retrieval (e.g., Allen et al., 2004; Light, 1991; Spaniol, Madden, & Voss, 2006). Indeed, this age-related sparing for semantic retrieval appears to hold for visual word recognition (Allen et al., 1993), semantic priming (Laver, 2009), and fact retrieval from mental arithmetic (Allen, Bucur, et al., 2005; Arnaud, Lemaire, Allen, & Michel, 2008; Geary, Frensch, & Wiley, 1993).

Unlike word frequency effects, which are relatively consistent across adult age, lexical decision case-mixing effects are often larger for older adults than for younger adults (Allen et al., 1993; Allen, Smith, et al., 2002). These results suggest that older adults show a holistic bias in visual word recognition relative to younger adults. That is, when forced to use letter-level codes during word encoding (i.e., mixed-case presentation), older adults show much greater slowing than when they can use holistic codes (lowercase presentation). One influence on this pattern of results is age-related decline in visual-sensory processing (Schneider & Pichora-Fuller, 2000; Scialfa, 2002—for example, Wingfield, Tun, & McCoy, 2005, have found that there is a resource cost at later stages of processing for more effortful processing at the sensory level); another is the decreased familiarity of the spatial structure of mixed-case items (James & MacKay, 2007, and MacKay & James, 1994, have emphasized the importance of stimulus familiarity for older adults). Our central hypothesis is that these influences, along with the required superposition of separate analytic letter-level codes into a single word unit when whole-word normalization fails, combine to increase the time required by older adults during encoding, but not during lexical access. Thus, we predict that case mixing will present a particularly challenging situation for older adults relative to younger adults, but that word frequency will not.

Research using naming or pronunciation tasks also suggests that older adults are relatively more biased toward holistic visual word recognition than younger adults (Spieler & Balota, 2000). Some researchers believe that a naming task may have certain advantages over a lexical decision task, as a measure of word recognition, due to the influence of decision-level effects in lexical decision (Balota & Chumbley, 1984; although see Allen et al., 2005). Age effects in word frequency for word naming have varied across studies, with some studies reporting an age-related increase in the effect of word frequency (Balota & Ferraro, 1993; Spieler & Balota, 2000), and others reporting an age constancy for word frequency (Balota et al., 2004; averaged across objective and subjective measures of word frequency).

The Present Experiments

The goal of the present study was to simultaneously examine the effect of increased adult age on case type, word frequency, and phonological regularity to determine more precisely why older adults slow down relative to younger adults in visual word recognition. If older adults are especially penalized when forced to process words letter-by-letter (analytically) and then to bind/superpose the individual letter-level codes into pseudo-whole-word codes (see Allen et al., 1995) (due to either an unfamiliar global spatial-frequency pattern, such as with mixed-case stimuli, or because of older adults' poorer retinal resolution of lower-spatial-frequency information), then they should show larger case-mixing effects than younger adults, but there should be no age differences in word frequency or phonological regularity. We used a naming task rather than a lexical decision task because naming requires phonological production—thereby increasing the sensitivity of detecting potential age differences in problems of integrating addressed- and assembled-route information. In addition, orthographic encoding and lexical access, as well as dual-route integration processing, have not been manipulated in the same study. By using the present factorial design, our goal was to apply the joint method of agreement and difference (essentially converging operations; Garner, Hake, & Eriksen, 1956) with the goal of isolating age differences.

We hypothesize that lexical access (semantic memory retrieval) remains stable with healthy aging, but that orthographic perceptual encoding (input), response selection (response decision), and response execution (output) decline with increased adult age (Allen et al., 1995; Lien et al., 2006; Hartley, 2001). Our present design includes a perceptual encoding manipulation, along with separate lexical access (word frequency) and phonological (regularity) manipulations, which allows us to make precise tests of our process-specific model of visual word recognition. Although age-related decline in assembled processing may occur for unfamiliar stimuli (James & MacKay, 2007; MacKay & James, 2004), in the present context, which used single-syllable words, we hypothesize that there will be no age differences in the effects of phonological regularity or word frequency. If older adults show larger word frequency effects, but similar case-mixing and phonological regularity effects (e.g., Balota & Ferraro, 1993, 1996), then this would replicate earlier research supporting a memory retrieval locus and falsify our perceptual encoding deficit hypothesis. For example, Balota and Ferraro found evidence that older adults had a less-efficient semantic memory retrieval (as measured by larger word-frequency effects) than younger adults, and that older adults also experienced a lack of inhibitory control for the assembled (phonological) route (i.e., they sometimes used the assembled route to name exception words, even though exception words cannot be pronounced correctly using this route). However, we predict that there will be no age differences in lexical access (word frequency effects), or in phonological processing (no age differences in regularity effects), or in the processing of orthographically regular words with neighbors that are pronounced irregularly, but that older adults will show orthographic encoding deficits when forced to use analytic codes (e.g., process words presented in mixed case). Hence, we are predicting an orthographic encoding deficit when older adults are forced to use smaller perceptual units and then to superpose these individual letters into a whole-word code, but that semantic memory retrieval (lexical access) and the synchronization of the addressed and assembled routes (as measured by naming performances for exception, regular, and regular-inconsistent words) will be relatively unaffected by adult age. If these hypotheses are correct, then older adults' performance decrements should be isolated at the orthographic encoding stage (as indexed by the case type manipulation), but there should be no appreciable age differences in lexical access (as indexed by the word frequency manipulation) or phonological assembly (regularity manipulation).

EXPERIMENT 1

Methods

Participants

A total of 40 individuals completed Experiment 1 as a single 30-min session. All participants were screened for near visual acuity of at least 20/40 using the Rosenbaum Pocket Vision Screener. Twenty healthy younger adults ($M = 23.3$ years, range = 18–33) participated for course credit, and 20 healthy, community-dwelling older adults ($M = 73.2$ years, range = 61–86) were paid $20 for their participation. There were no significant group differences in years of education (younger adults $M = 15.3$ years, older adults $M = 15.6$ years). Younger adults exhibited higher Wechsler Adult Intelligence Scale—Revised (WAIS-R; Wechsler, 1981) Digit-Symbol Substitution subtest scores ($M = 71.0$) than older adults ($M = 51.0$), $F(1, 38) = 42.12$, $p < .0001$. With regard to Mill Hill Vocabulary Test (Raven, Raven, & Court, 1997) scores, though, older adults showed higher scores ($M = 22.5$) than younger adults ($M = 18.2$), $F(1, 38) = 14.98$, $p < .0001$.

Stimulus Materials

We used 84 (out of the total of 90) words from the Seidenberg et al. (1984, Experiment 4) stimulus list of monosyllabic words so that there would be equal numbers of stimuli in each Case Type × Word Frequency × Regularity/Consistency Category. The present 84-word corpus consists of 28 exception words, 28 regular-inconsistent words, and 28 regular-consistent controls. There were 14 high-frequency and 14 low-frequency words for each of the three conditions (median frequencies were based on Carroll, Davies, & Richman, 1971: exception: high = 707, low = 17; regular-inconsistent: high = 672, low = 24; regular controls: high = 638, low = 18; see Seidenberg et al., 1984, Experiment 4, for additional details). Half of the words in each basic condition (exception, regular-inconsistent, and regular-consistent control) were assigned to the mixed-case condition and the remaining half were assigned to the consistent lowercase condition for 10 participants from both age groups, and the remaining participants received the other half of the words presented in mixed case. This yielded seven trials in each of 12 cells, derived from the combination of three conditions, two levels of word frequency, and two case types.

Apparatus and Procedure

Participants were tested on either a desktop personal computer with a 15-inch computer monitor. Timing and stimulus presentation were both controlled by the Micro Experimental Laboratory (MEL) software (Schneider, 1988).

The display was placed approximately 50 cm in front of participants so that each letter subtended a visual angle of 0.28° horizontally and 0.56° vertically (total horizontal visual angle of 1.85° for the longest possible six-letter word). All words were centered and presented in white letters on a black background.

Naming responses were collected using a Radio Shack microphone connected to the MEL response box (which was also connected to the computer). Pronunciation onset time was computed as the delay between word presentation onset and naming onset. On each trial, the experimenter entered a 1 (correct response), a 0 (incorrect response), or a 5 (contaminated trial, e.g., the participant coughed). Accuracy analyses did not include contaminated trials (less than 1% of all trials). Participants were instructed to name each visually presented word as quickly and as accurately as possible. Stimuli remained on the screen until the participant's response.

Results

The mean reaction time (RT) and error results are presented in Table 1 as a function of group (younger and older adults), condition (exception, regular-inconsistent, regular-consistent controls), word

Table 1. Mean reaction time (in milliseconds) (standard deviations) and mean error rate (mean percent error) (standard deviations) for Experiment 1 as a function of group (younger and older adults), condition (exception, regular-inconsistent, and regular control), case type (lowercase vs. mixed case), and word frequency (high vs. low)

Condition/regularity	Exception	Regular-inconsistent	Control
Young			
Lowercase			
High frequency			
RT	577 (71)	553 (50)	589 (92)
Error	5.0 (.07)	5.0 (.10)	4.3 (.08)
Low frequency			
RT	691 (117)	601 (72)	592 (75)
Error	17.9 (.14)	6.4 (.09)	5.7 (.09)
Mixed case			
High frequency			
RT	610 (96)	577 (71)	617 (118)
Error	3.6 (.08)	6.4 (.10)	6.4 (.10)
Low frequency			
RT	700 (92)	606 (84)	596 (69)
Error	21.4 (.14)	6.4 (.12)	7.1 (.10)
Mean RT	644	584	598
Mean Error	12.0	6.0	5.9
Older			
Lowercase			
High frequency			
RT	761 (144)	753 (158)	767 (172)
Error	7.1 (.14)	7.9 (.10)	5.7 (.09)
Low frequency			
RT	911 (249)	820 (226)	785 (155)
Error	20.7 (.17)	7.9 (.10)	6.4 (.10)
Mixed case			
High frequency			
RT	847 (200)	804 (170)	862 (209)
Error	5.7 (.12)	7.1 (.11)	8.6 (.11)
Low frequency			
RT	960 (326)	867 (235)	890 (218)
Error	23.6 (.20)	10.0 (.11)	11.4 (.11)
Mean RT	870	811	826
Mean Error	14.3	8.2	8.0

frequency (high vs. low), and case type (mixed case vs. consistent lowercase; odd numbers are lowercase and even numbers are mixed case). Data trimming used RT boundaries of 100 to 3000 ms for younger adults and 100 to 4000 ms for older adults eliminated approximately 3% of the correct responses.

Latency Data

There were main effects for group $F(1, 38) = 27.07$, $p < .001$ (younger adults $M = 609$ ms, older adults $M = 835$ ms), word frequency, $F(1, 38) = 55.87$, $p < .001$ (high frequency $M = 693$ ms, low frequency $M = 752$ ms), and case type, $F(1, 38) = 19.55$, $p < .001$ (mixed case $M = 746$ ms, lowercase $M = 699$). These main effects were qualified by a Group × Case Type interaction, $F(1, 38) = 7.34$, $p < .05$. The increase in RT for mixed-case words relative to lowercase words was greater for older adults (73 ms) than for younger adults (20 ms).

There was also a main effect for condition, $F(2, 76) = 19.47$, $p < .001$ (exception $M = 756$ ms, regular-inconsistent $M = 698$ ms, regular control $M = 712$ ms). Exception words took longer than regular-inconsistent words ($p < .001$), and regular controls ($p < .001$), but regular-inconsistent latencies did not differ significantly from regular controls ($p = .07$).

The main effect for condition was qualified by a Condition × Frequency interaction, $F(2, 76) = 17.55$, $p < .001$. This occurred because the regularity effect was more pronounced for lower-frequency words (exception $M = 815$ ms, regular-inconsistent $M = 724$ ms, regular control $M = 716$ ms) than for higher-frequency words (exception $M = 698$ ms, regular-inconsistent $M = 672$ ms, regular control $M = 709$ ms). When we analyzed lower-frequency words separately, the main effect for condition became more pronounced, $F(2, 76) = 274.48$, $p < .001$. However, when just higher-frequency words were included, the main effect for condition was attenuated, $F(2, 76) = 8.42$, $p < .01$, but this was because control words took longer to name than regular-inconsistent words ($p < .001$), as did exception words ($p < .001$), but controls did not differ from exception words ($p = .38$).

Error Data

For the error analyses, there was a main effect for frequency, $F(1, 38) = 30.93$, $p < .001$ (high frequency $M = 6.1\%$, low frequency $M = 12.1\%$). Younger adults and older adults did not differ significantly in naming errors. There was a main effect of condition, $F(2, 76) = 16.89$, $p < .001$ (exception $M = 13.1\%$, regular-inconsistent $M = 7.1\%$, control $M = 7.0\%$), and this was qualified by a Condition × Frequency interaction, $F(2, 76) = 30.13$, $p < .001$. This interaction resulted from a regularity effect occurring for low-frequency words (i.e., exception words showed higher error rates than the other two categories for lower-frequency words but not for higher-frequency words). Simple effect tests performed on each level of word frequency indicated a significant condition effect for low-frequency words, $F(2, 76) = 33.54$, $p < .001$, but not for high-frequency words.

Slowing Analyses

To examine age-related slowing, we standardized participants' latencies for each task condition by subtracting individual means for all conditions (each participant's grand mean) from individual cell means, and then divided by an individual's grand standard deviation (Faust, Balota, Spieler, & Ferraro, 1999). This procedure is designed to place younger and older adults on the same latency scale (adjust for the fact that older adults typically have longer responses that can exacerbate interactions with age). The Case Type × Age Group interaction persisted, $F(1, 38) = 8.83$, $p < .01$. Consequently, for Experiment 1, there is evidence of process-specific effects in the older adults' latency data.

Correlational Analyses with Vocabulary and Education

Because we found equivalent word frequency effects for younger and older adults, but Balota and Ferraro (1993, 1996) found larger age differences for older adults, we wanted to confirm that these results were not the result of differential vocabulary score criteria across studies. Balota and Ferraro (1996) equated vocabulary scores across age, whereas in both of the present experiments we equated education levels across age, but our older adults showed higher vocabulary scores than did younger adults. Therefore, a question of interest is whether vocabulary scores are correlated with word frequency effects, condition (exception, regular-inconsistent, or control words), or case type. Correlational analyses for Experiment 1 showed that vocabulary scores and education were not significantly correlated with word frequency, condition, or case type (all p's $> .10$). We also repeated these same correlational analyses separately by age group, and, once again, neither vocabulary scores nor education were correlated with the effects of word frequency, condition, or case type (all p's $> .6$).

Discussion

The results for Experiment 1 show case-mixing effects that were more pronounced for older adults than for younger adults, but no age differences in word frequency effects or phonological regularity effects. The Age × Case Type interaction was statistically significant when raw latencies and standardized latencies (Faust et al., 1999) were used as dependent variables, so this effect was not the result of generalized slowing. Furthermore, we observed robust regularity effects for RT and errors, and these effects occurred primarily for lower-frequency words and were consistent across age group. Consequently, the results from Experiment 1 suggest that semantic memory retrieval (as measured by word frequency effects) and phonological processing (as measured by regular and consistency effects) remain intact in cognitively healthy older adults (relative to younger adults). However, when older adults are forced to process words analytically (as component letters rather than as multiletter units), then older adults take longer than younger adults to orthographically encode words in preparation for naming. These results suggest that older adults are slower than younger adults in naming visually presented words because older adults are less efficient at the component processes involved in encoding component letters and then binding/superposing these component letters into a word-level code (Allen, Smith, et al., 2002).

We failed to observe Consistency × Frequency interactions. These results replicate the results of Taraban and McClelland (1987, Experiments 1a and 1b) and Balota and Ferraro (1993) who also failed to find performance interactions across these two variables.

Consequently, the results from Experiment 1 favor the orthographic encoding deficit locus of age differences in visual word recognition. The present word frequency results (and to a lesser extent, regularity error results—we found additivity between age and regularity errors, although we not able to separate error types) are inconsistent with those observed in the Balota and Ferraro (using the same Seidenberg et al., 1984, stimulus set). Our observed additivity between word frequency and age cannot be attributed to the fact that the present older adults showed higher vocabulary scores than younger adults because these scores were not correlated with word frequency RT. Because of the importance of this effect to our present interpretation, though, we decided to conduct a replication experiment. Consequently, the results from Experiment 1 extend the earlier literature on age differences in visual word recognition by providing simultaneous support for an orthographic encoding deficit and evidence against age deficits in semantic memory retrieval/lexical access or phonological encoding deficits on the part of older adults.

EXPERIMENT 2

For Experiment 2, we used the larger Taraban and McClelland (1987) stimulus set (192 words rather than 84) to see if we could replicate the results case type, word frequency, and regularity results from

Experiment 1. Although Taraban and McClelland (Experiments 1a and 1b) failed to find a significant effect for consistency, this stimulus set also controls for initial phonemes for exception, regular, and regular-inconsistent words, whereas the Seidenberg et al. (1984) stimulus set does not (see Taraban & McClelland, 1987). If our perceptual encoding hypothesis is correct, then older adults should persist in showing an Age × Case Type interaction in Experiment 2, but age should not interact with word frequency or phonological regularity. However, both age groups should show Phonological Regularity × Word Frequency interactions indicating that they experienced more assembled-route interference for lower-frequency words than for higher-frequency words when naming exception words (relative to regular controls or regular inconsistent words).

Methods

Participants

A total of 120 individuals participated in Experiment 2. Sixty healthy younger adults ($M = 23.1$ years, range = 18–35) who were University of Akron psychology undergraduates participated for course credit. Sixty healthy, community-dwelling older adults ($M = 71.9$ years, range = 61–86) were paid $20 for their participation.

Participants reported no group differences in years of education (younger adults $M = 14.6$ years, older adults $M = 15.0$ years) ($p = .16$). Younger adults exhibited higher raw scores on the WAIS-R (Wechsler, 1981) Digit-Symbol Substitution subtest ($M = 70.7$) than older adults ($M = 53.6$), $F(1, 118) = 70.06$, $p < .0001$. With regard to Mill Hill Vocabulary Test (Raven et al., 1997) scores, though, analysis of variance (ANOVA) suggested that older adults showed higher scores ($M = 20.17$) than younger adults ($M = 17.61$), $F(1, 118) = 21.72$, $p < .0001$.

Stimulus Materials

The Taraban and McClelland (1987) stimulus list of 192 monosyllabic words was used in the present study. This corpus consists of 48 exception words, 48 matched exception controls, 48 regular-inconsistent words, and 48 matched regular-inconsistent controls. Control words were matched on the basis of word and bigram frequency, initial phoneme, and length. There were 24 high-frequency and 24 low-frequency words for each of the four conditions (mean Kučera & Francis, 1967, frequency by condition: exception: high = 1271, low = 20; exception control: high = 1172, low = 20;

regular-inconsistent: high = 398, low = 11; regular-inconsistent control: high = 409, low = 13). Half of the words in each basic condition (exception, exception control, regular-inconsistent, and regular-inconsistent control) were assigned to the mixed-case condition and the remaining half were assigned to the consistent lowercase condition. Forty participants in each age group received one assignment of case type to stimuli, and the remaining 20 participants in each age group received the other half of the words in mixed case. This resulted in 12 trials in each 4 (condition) × 2 (word frequency) × 2 (case type) cell.

Apparatus

The methods used for display presentation and recording responses, and procedure, were the same as those used in Experiment 1.

Results

The mean reaction time (RT) and error (mean percent error) data are presented in Table 2 as a function of age group, condition (exception, exception control, regular-inconsistent, regular-inconsistent control), word frequency (high vs. low), and case type (mixed case vs. consistent lowercase). Group was a between-subjects variable whereas all other variables were within-subjects. The data trimming procedure was the same as that used in Experiment 1 and eliminated fewer than 3% of the correct responses. We present separate analyses for exception versus exception control conditions and regular-inconsistent versus regular-inconsistent controls, to test for conspiracy effects (condition effects are not presented for overall analyses because there are frequency differences between exception and regular-inconsistent words—see Methods; these differences were not present in the Seidenberg et al., 1984, stimulus set).

Overall Performance

ANOVA of RT values yielded significant main effects for age group $F(1, 118) = 46.81$, $p < .001$ (younger adults $M = 634$ ms, older adults $M = 810$ ms), word frequency, $F(1, 118) = 76.05$ (high frequency $M = 698$ ms, low frequency $M = 746$ ms), and case type, $F(1, 118) = 94.29$, $p < .001$ (mixed case $M = 767$ ms, lowercase $M = 676$ ms). These main effects were qualified by a Group × Case Type interaction, $F(1, 118) = 16.71$, $p < .001$ (younger adults: mixed case = 660 ms − lowercase = 607 ms = 53 ms; older adults: mixed case = 875 ms − lowercase = 745 ms = 130 ms). The simple effects for group were significant for both case types, but were greater in

Table 2. Mean reaction time (in milliseconds) (and standard deviations) and mean error rate (in mean percent error) (and standard deviations) for Experiment 2 as a function of group (younger and older adults), condition (exception, exception-control, regular-inconsistent, and regular-inconsistent control), case type (lowercase vs. mixed case), and word frequency (high vs. low)

Condition/regularity	Exception	Exception-control	Regular-inconsistent	Regular-consistent control
Young				
Lowercase				
High frequency				
RT	582 (94)	584 (101)	613 (125)	585 (90)
Error	1.5 (.04)	3.5 (.06)	4.0 (.06)	3.3 (.06)
Low frequency				
RT	645 (142)	599 (88)	619 (96)	631 (127)
Error	4.4 (.07)	2.1 (.04)	4.2 (.06)	3.1 (.06)
Mixed case				
High frequency				
RT	636 (120)	625 (102)	650 (129)	647 (121)
Error	3.3 (.06)	2.3 (.04)	8.5 (.09)	5.6 (.05)
Low frequency				
RT	695 (205)	661 (141)	677 (150)	689 (148)
Error	5.0 (.06)	4.2 (.06)	4.4 (.07)	2.3 (.05)
Mean RT	639	617	640	638
Mean Error	3.5	3.0	5.3	3.6
Older				
Lowercase				
High frequency				
RT	720 (134)	721 (132)	749 (134)	721 (129)
Error	0.8 (.03)	2.5 (.04)	2.9 (.04)	2.5 (.04)
Low frequency				
RT	770 (153)	753 (147)	777 (149)	749 (138)
Error	2.1 (.04)	2.1 (.04)	1.7 (.04)	2.9 (.05)
Mixed case				
High frequency				
RT	818 (190)	809 (177)	859 (226)	844 (217)
Error	1.2 (.03)	5.4 (.06)	5.8 (.07)	5.6 (.07)
Low frequency				
RT	915 (297)	908 (297)	898 (270)	946 (254)
Error	2.5 (.04)	6.7 (.07)	4.8 (.07)	3.8 (.05)
Mean RT	806	798	821	815
Mean Error	1.6	4.2	3.8	3.7

magnitude for mixed case ($p < .01$) than for lowercase presentation ($p < .05$). There was also Group × Frequency interaction, $F(1, 118) = 4.17$, $p < .05$, but this interaction was qualified by a Group × Frequency × Case Type interaction, $F(1, 118) = 5.87$, $p < .05$. These interactions indicated that older adults showed larger word frequency effects for words presented in mixed case (younger adults: lower frequency = 680 ms – higher frequency = 639 ms = 41 ms; older adults: lower frequency = 917 ms – higher frequency = 833 ms = 84 ms), but not for words presented in lowercase (younger adults: lower frequency = 623 ms – higher frequency = 591 ms = 32 ms; older adults: lower frequency = 762 ms – higher frequency = 728 ms = 44 ms) (see Table 2). When just lowercase words were analyzed, there was no longer a Group × Frequency interaction, $F(1, 118) = 0.06$, $p = .81$.

For the overall error analyses, there was a main effect for case type $F(1, 118) = 70.85$, $p < .001$ (lowercase $M = 3.2\%$, mixed case $M = 5.6\%$), and the Group × Case Type interaction was significant, $F(1, 118) = 7.00$, $p < .01$ (younger adults: lowercase $M = 3.6\%$, mixed case $M = 5.3\%$; older adults: lowercase = 2.8%, mixed case $M = 6.0\%$). Younger adults and older adults did not differ significantly in naming errors ($p = .88$).

Exception Latencies and Errors

To examine regularity effects, we analyzed just exception words and their matched controls. For the latency analyses, the main effect for regularity was significant, $F(1, 118) = 11.16$, $p < .01$ (exception $M = 722$ ms, regular control $M = 707$ ms), and there was a Regularity × Frequency interaction, $F(1, 118) = 6.45$, $p < .05$, reflecting the finding that the regularity effect was present for lower-frequency words (exception $M = 756$, regular control $M = 730$) but not for higher-frequency words (exception $M = 689$, regular control $M = 684$).

Error rate on the exception and associated control trials was relatively low (1.5% to 5.0%; Table 1) and in accord with the RT data.

Regular-Inconsistent Latencies and Errors

To examine consistency effects, we analyzed just regular-inconsistent words and their matched controls. For the latency data, there was a significant Consistency × Case Type interaction, $F(1, 118) = 9.25$, $p < .01$. This occurred because there was a consistency effect (i.e., increase in RT for regular-inconsistent words relative to their controls) for words presented in lowercase (12 ms, $p < .05$), but not for words presented in mixed case. This two-way interaction was qualified by a Group × Condition × Frequency × Case Type interaction, $F(1, 118) = 5.25$, $p < .05$. To interpret this interaction, we conducted separate analyses on case type. For lowercase words only, there was a simple effect of condition, $F(1, 118) = 10.98$, $p < .01$, but no other interactions with condition reached statistical significance (although the Group × Condition interaction approached significance, $p = .0648$). For the lowercase words, participants took longer to name regular-inconsistent words ($M = 689$) than controls ($M = 671$). However, for words presented in mixed case, there was a Condition × Frequency interaction, $F(1, 118) = 5.32$, $p < .05$. In order to interpret this simple effect, we conducted separate analyses by word frequency. For higher-frequency words, there was no simple effect for condition ($p = .36$). However, for lower-frequency mixed-case words, there was a simple effect for condition, $F(1, 188) = 6.07$, $p < .05$ (regular-inconsistent $M = 788$, control $M = 818$). Thus, participants responded more slowly to regular-inconsistent words than to regular-inconsistent controls for lowercase stimuli, but they showed faster responses to regular-inconsistent, lower-frequency words presented in mixed case relative to controls (refer to Table 2).

There was also a Group × Consistency interaction for errors, $F(1, 118) = 5.43$, $p < .05$. This interaction occurred because older adults showed a consistency effect (regular-inconsistent $M = 5.2\%$, regular control $M = 4.6\%$), but younger adults did not (regular-inconsistent $M = 5.6\%$, regular control $M = 6.8\%$).

Slowing Analyses

As we did in Experiment 1, we controlled for general slowing to see if the same pattern of interactions with age would persist in Experiment 2. As before, we used the latency standardization procedure recommended by Faust et al. (1999) in which individual's latencies are standardized by subtracting individuals' overall means from their cell means and then dividing by individuals' overall standard deviations. In this z-RT analysis, the Group × Case Type interaction persisted, $F(1, 118) = 4.93$, $p < .05$. Thus, as was the case in Experiment 1, the older adults' larger case-mixing effects were not the result of scale effects due to generalized slowing.

Discussion

The case type and word frequency effects for Experiment 2 were in accord with those from Experiment 1. That is, older adults performed relatively more poorly than younger adults on words presented in mixed case compared to words presented in consistent lowercase letters, and there were no age differences in word frequency effects for words presented in lowercase. These results are consistent with an orthographic encoding rather than a semantic memory retrieval deficit for older adults. Thus, even when case type, word frequency, and phonological regularity were all varied in the same aging experiment, just case type interacted with age—thereby replicating the results of Experiment 1 while still employing the rigorous experimental methods of the joint method of agreement and difference.

In Experiment 2 (as in Experiment 1), participants showed a regularity effect for lower-frequency words but not higher-frequency words. That is, exception words took longer to name than regular control words for lower-frequency stimuli but not for higher-frequency stimuli. The key finding in both of the present experiments with regard to phonological regularity was that older adults do not seem to have a lack of inhibitory control over the assembled route, but rather, a seeming lack of activation strength in the assembled route.

With regard to age-related slowing, the present results suggest that age effects are isolated within specific processing stages (particularly stimulus encoding of unfamiliar spatial units), and cannot be explained entirely by general slowing. That is, if general slowing accounted for the Age × Case Type interaction, then this interaction should have been eliminated by the z-transformed analysis—but this interaction persisted even after the latencies were z-transformed.

Consequently, the present results do suggest that older adults are particularly disadvantaged when they are forced to recognize a visually presented word analytically and then to attentionally bind/superpose the component letters into a whole-word code. However, there were no age differences in lexical access efficiency (as measured by word frequency). Although older adults did show larger word frequency effects for words presented in mixed case in Experiment 2 (but not for Experiment 1), there were no age differences in word frequency effects when words were presented in a familiar spatial frequency (i.e., consistent lowercase). This suggests that older adults took relatively longer to orthographically encode lower-frequency words presented in mixed case than higher-frequency words presented in mixed case.

Both age groups showed a relatively larger phonological regularity effect for lower-frequency words (compared to higher-frequency words). Also, we observed a consistency effect for words presented in lowercase (regular-inconsistent words were pronounced more slowly than control words), but regular-inconsistent, lower-frequency words presented in mixed case were actually pronounced more rapidly than were control words. The key result here was that consistency effects for lowercase stimuli were found for both age groups, and this effect did not interact with age.

GENERAL DISCUSSION

Although previous research on visual word recognition has consistently found that older adults slow down relative to younger adults, there is little agreement with regard to why this slowing occurs. Some investigators have claimed that age effects are due to phonological deficits (e.g., MacKay & James, 2004), others have claimed that this slowing is the result of less efficient semantic memory retrieval/lexical access on the part of older adults (Balota & Ferraro, 1993, 1996), and yet others have proposed that older adults are slower in visual word recognition due to decrements in orthographic encoding and attentional binding/superposition of component codes into whole-word codes (Allen et al., 1991, 1993, 2002). The present research was designed to provide clarification of the locus/loci of this deficit(s) by manipulating task difficulty of all three of the processing stages (phonological, lexical access, and orthographic encoding) in the same experiments using word-naming tasks. This allowed us to test whether the locus (or loci) of age differences in naming were at the orthographic encoding stage (case type), at semantic memory retrieval (word frequency), or at the level of integration between the dual addressed and assembled routes (as measured by phonological regularity and consistency effects), or at multiple stages (as would be predicted by general slowing). We found that the case-mixing manipulation was the only one of the three manipulations that showed appreciable age effects across both experiments. Although both age groups showed case-mixing effects, the processing disadvantage for mixed-case presentation was more pronounced for older adults relative to younger adults in both experiments. Also, older adults' perceptual encoding deficit for both experiments survived a z-transformation of RT, indicating that at least some aspect of the age-related case-mixing effects is of greater magnitude than predicted by a one-dimensional (general) slowing model.

These results are consistent with an orthographic encoding deficit. That is, older adults may be relatively more efficient at encoding larger units of information (lowercase presentation) than smaller units of information (mixed-case presentation) (Allen et al., 1993; Allen, Smith, et al., 2002). When older adults are required to encode words letter-by-letter and then attentionally bind/superpose these component codes into a whole-word code, then seniors are relatively more disadvantaged by this type of processing than are younger adults. Thus, the present data are consistent with a decision complexity advantage theory of cognitive aging (Allen, Smith, et al., 2002) in which older adults apparently can attenuate perceptual encoding deficits by using larger units of analysis (in this case, multiletter units rather than individual letters). However, when older adults cannot encode information using larger perceptual units, they are particularly disadvantaged in encoding words relative to younger adults.

In both of the presently reported experiments, we found consistent word frequency effects across age. We did find larger word frequency effects for older adults in Experiment 2 for mixed-case presentation, but not for lowercase presentation. Thus, this suggests that case mixing was the locus of this effect rather than lexical access. These results are at odds with a semantic memory retrieval deficit model of age differences in naming (e.g., Balota & Ferraro, 1993). The present results, though, are consistent with those obtained by Balota et al. (2004), Allen et al. (1993; Allen, Smith, et al., 2002) who all found consistent word frequency effects across age (Balota et al., 2004, found no age differences in objective words frequency, but they did find age differences in subjective word frequency). Furthermore, using a dual-task methodology (in which Task 2 was a lexical decision task that varied word frequency), Allen, Lien, et al. (2002) and Lien et al. (2006) found evidence suggesting that older adults were more efficient at lexical access than were younger adults. Finally, Spaniol et al. (2006) used diffusion modeling to examine age differences in episodic and semantic memory. They found age differences in a measure of the efficiency of memory retrieval (drift rate) for episodic memory, but not for semantic memory. Consequently, the present study and many earlier studies have found that semantic memory retrieval is not appreciably affected by increased adult age. Note that this general finding of semantic memory retrieval sparing with increased adult age is consistent with the idea that older adults would not show larger word frequency effects than younger adults.

We believe that the present age effects across case type, word frequency, and phonological regularity (exception vs. regular words) are best interpreted using the model outlined in Figure 1. We assume that individuals process visually presented words in a naming task using four routes (analytic and holistic orthographic and phonological routes). The addressed orthographic routes lead to word identification but also can result in word naming through the use of addressed phonology (i.e., the relationship between orthography and phonology is “looked up” in semantic memory). Because the holistic (whole-word) route can directly access the lexicon, and because it is more efficient (it encodes the word “jump” as a single spatial-frequency unit rather than four separate spatial-frequency units: “j” “u” “m” “p”—thereby obviating the need to superpose component letters into a whole-word code), it tends to win the stochastic race if the spatial-frequency pattern of the word unit is familiar. However, case mixing "handicaps" the holistic channel (e.g., the spatial-frequency pattern of "jUmP" is unfamiliar) but not the analytic channel (i.e., the spatial-frequency patterns of individual letters are still familiar in "jUmP"). Thus, case mixing using letters only is thought to allow us to examine analytic processing without interference from holistic processing (Allen et al., 1995, 2009).

The phonological routes in Figure 1 are also assumed to process words by GPC rules that convert orthography (either analytic single graphemes, or letters, or holistic multiletter units such as onsets and rimes) into phonological codes through an assembly process (although not required for word recognition and reading, these routes are used in speaking so are presumed to be automatic). It is assumed that the phonological routes tend to be slower than the orthographic routes for higher-frequency words because the assembly process is the same for all word-frequency levels, but that the activation threshold for the lexical pathways decreases as word frequency increases. Thus, the two pathways (in the present model, four routes) have more similar output times for lower-frequency words (Balota & Ferraro, 1993; Besner & Johnston, 1989; Herdman et al., 1999). It is further assumed that the assembled, phonological routes can process words that are regular (e.g., beam, seam, team, ream), or regular-inconsistent (e.g., save, cave, gave), but not exception words like "have" (e.g., GPC rules that work for "cave" will not result in correct pronunciation of "have"). It is assumed that the phonological/assembled routes inhibit exception words like "have," whereas the lexical channels can pronounce exception words because they retrieve stored orthographic-to-phonological relations. For higher-frequency words, the orthographic channel wins the processing race so no appreciable interference occurs (Besner & Johnston, 1989). However, for lower-frequency words, orthographic and phonological channels have similar output times (indeed, even the analytic, orthographic route has similar output times as the holistic, orthographic route for lower-frequency words—see Allen & Emerson, 1991). The similar output times for phonological and orthographic routes for lower-frequency words results in interference for exception words because the phonological route "disagrees" with the orthographic route(s) with regard to how to pronounce exception words.

In the present model, both younger and older adults processed words for naming in similar ways resulting in approximately equivalent word frequency and phonological regularity effects across age (although older adults did not show regularity effects for low-frequency words in Experiment 2, but younger adults did). These results suggest that there is age-related sparing of semantic memory retrieval and in the integration of addressed- and assembled-route information (because there were no observed increases in assembled-route interference for older adults). However, when individuals were forced to use analytic encoding (by mixing case so that the holistic channel could not interpret the spatial-frequency pattern of multiletter units), this was particularly cumbersome for older adults. This finding implicates perceptual encoding as the primary locus of age differences in visual word recognition time, and implies that older adults are particularly slowed by less-efficient normalization, or image enhancement, due to age-related changes in visual sensory processing (Schneider & Pichora-Fuller, 2000; Scialfa, 2002). The greater case-mixing effect for older adults is also likely due to a relatively greater cost for superposing the component letter-level codes into a whole-word code for mixed-case stimuli.

Earlier studies have found some evidence of semantic memory retrieval and dual-route integration deficits (as measured by increased naming errors for exception errors) for older adults. For example, Balota and Ferraro (1993) interpreted their results of larger word frequency effects for older adults along with equivalent regularity effects for RT but increased regularity errors for older adults across age in terms of an inhibitory control deficit framework. This alternative explanation (from our present model) predicts that older adults have less-efficient addressed processing than younger adults (accounting for larger word frequency effects for older adults), as well as a lack of inhibitory control for the assembled route (i.e., they are prone to use the assembled route to name exception words, even though exception words cannot be pronounced correctly using this route because exception words have irregular GPC relations). We were unable to replicate their results, however (although in fairness to Balota and Ferraro, we did not code for error types in naming in the present experiments). That is, we did not find age differences in word frequency effects or higher error rates for older adults even in Experiment 1 (very strange exception words). This discrepancy cannot be attributed to differences in vocabulary scores across studies because we failed to find a significant correlation between vocabulary scores and word frequency (see Experiment 1; and MacKay & James, 2004, also failed to find a significant correlation between vocabulary scores and word frequency effects). Instead our results suggest that older adults may have less efficient perceptual encoding.

Why Are Phonological Regularity and Orthographic Consistency Effects So Variable?

Clearly this is a perplexing situation. Seidenberg et al. (1984) found evidence for Consistency × Frequency interactions (poorer performance for regular-inconsistent words than for regular controls—particularly for lower-frequency words), but Taraban and McClelland (1987) did not find appreciable consistency effects (Taraban & McClelland, 1987, Experiments 2 and 3, did find consistency effects when they primed target words with the irregular neighbor but not when they simply presented the target words, Experiments 1a and 1b). Furthermore, Herdman et al. (1999) (who compared just exception word naming to regular word naming) found Case Type × Regularity effects for higher-frequency words but not for lower-frequency words, yet Besner and McCann (1989) found the very opposite effect. Finally, we found no Case Type × Regularity × Word Frequency interaction. As noted by Herdman et al., our results can be interpreted by assuming that participants were biased toward lexical routes (in which case all three effects should be additive; see Besner, 1990). However, it remains a paradox as to why Consistency × Frequency interactions are not always present (the present study; Balota & Ferraro, 1993; Taraban & McClelland, 1987—although we did observe consistency effects for lowercase words in Experiment 2 in the present study), or why regularity effects sometimes affect lower-frequency words more than higher-frequency words (Besner & McCann, 1987) or vice versa (Herdman et al., 1999). What does seem to be clear, though, is that in the present two experiments, age differences were moderated by case type and not by phonological regularity or word frequency.

Multiroute Versus Interactive Models

The model that we have proposed to account for naming performance has a symbolic form (see Figure 1). That is, we assume that words are represented in a mental lexicon and that functionally serial discrete stages exist (e.g., encoding, lexical access, response selection, response execution). Alternatively, one can model language processing through the use of subsymbolic, interactive, neural-network frameworks (e.g., the Transmission Deficit Hypothesis, or TDH; see James & MacKay, 2007; MacKay & James, 2004). It is beyond the scope of this paper to debate the relative merits of these two cognitive architectures, but our present model presented in Figure 1 can be implemented as a hybrid interactive model (see Allen et al., 2009, for a cognitive neuroscience model). Both the present model and the TDH views account for age differences in language processing in the same manner—older adults show deficits for more unfamiliar information. In our model, we emphasize that age differences in perceptual encoding, particularly for smaller pieces of information, account for longer visual word recognition times in older adults. Alternatively, MacKay and colleagues emphasize how phonological activation nodes for unfamiliar information (such as pronounceable nonwords) cause age-related asymmetries (see James & MacKay, 2007).

Conclusion

The major finding from the present study is that healthy older adults show orthographic word encoding deficits on a visual word-naming task in spite of the fact that there were no appreciable age differences in word frequency or phonological regularity (spelling-to-sound correspondence)—suggesting that age differences in naming are isolated at encoding. Because age did not interact with word frequency or with phonological regularity effects, this suggests that semantic memory retrieval and integration of dual-route information are not appreciably affected by increasing adult age.

It is possible that older adults attempt to compensate for their encoding deficit in a bottom-up manner (in the sense that computational spatial-frequency signal processing is used to form perceptual codes rather than alluding to top-down contextual information) by using progressively larger units of analysis through increased skill—what we have referred to as the decision complexity advantage (Allen et al., 1993; Allen, Smith, et al., 2002). The decision complexity advantage predicts that, as long as the theoretical capacity of the system is not overwhelmed, humans perform optimally when they use as large of units of analysis as possible. It appears that older adults, in particular, take advantage of the availability of larger perceptual units (perhaps in large part because it does not require attentional binding of component letters into whole-word codes). Interestingly, this idea is consistent with the aging literature on top-down attentional control (Madden, 2007; Madden, Spaniol, Bucur, & Whiting, 2007), except the present model emphasizes bottom-up rather than top-down processing. In both cases, there is evidence that older adults use compensatory processing later on in the information-processing sequence of stages in an attempt to minimize age differences in sensory processing.

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