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Age-linked Declines in Retrieving Orthographic Knowledge: Empirical, Practical, and Theoretical Implications

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Abstract

This study develops a theory of how aging affects the retrieval of orthographic knowledge based on the Transmission Deficit hypothesis of MacKay and Burke (1990). To test predictions of this theory, three groups of normal, healthy adults, mean ages 19, 67, and 77 years old, heard a tape-recorded series of difficult-to-spell words of high and low frequency, spoken slowly, clearly and repeatedly, and simply wrote down each word at their own pace. With perceptual errors and differences in vocabulary factored out, misspellings increased with aging, especially for high-frequency words. In addition, data from a metamemory questionnaire indicated that the oldest adults were aware of their declining ability to spell.

These findings were not related to general slowing, to educational factors, to rated quality of prior training on spelling skills, to hours per week spent reading, writing, or solving crossword puzzles, or to age-linked declines in the ability to monitor or detect errors in their responses. However, the results fit predictions of the Transmission Deficit theory developed here, and suggested an age-linked decline in the retrieval of orthographic knowledge that resembles age-linked declines in spoken word retrieval observed in many other studies. Practical implications of this age-linked decline for conceptions of normal aging are noted.

Age-linked Declines in Retrieving Orthographic Knowledge: Empirical, Practical, and Theoretical Implications

Although many studies have examined how aging affects the retrieval of phonology during spoken language production (e.g., Albert, Heller, & Milberg, 1988; Au, Joung, Nicholas, Obler, Kass, & Albert, 1995; Balota & Duchek, 1988; Bowles, Obler, & Poon, 1989; Bowles & Poon, 1985; Burke, MacKay, Worthley, & Wade, 1991; Cohen & Faulkner, 1986; Liss, Weismer, & Rosenbek, 1990; Maylor, 1990; McCrae, Arenberg, & Costa, 1987; Mitchell, 1989; Nicholas, Obler, Albert, & Goodglass, 1985; Nicholas, Barth, Obler, Au, & Albert (1997); Rastle & Burke, 1996; Thomas, Fozard, & Waugh, 1977), no studies have directly examined how aging affects the retrieval of orthography, the corresponding level of written language production. However, effects of aging on the generation of letter strings, otherwise known as the ability to spell, are of interest on empirical, practical, and theoretical grounds. Empirically, age-linked declines in language production have been repeatedly demonstrated at phonological levels, and it is important to determine whether similar age-linked declines occur at orthographic levels. Practically, a demonstration of age-linked declines in spelling ability would help define the nature of normal aging and would support steps to evaluate and overcome the possible consequences of those declines. Theoretically, effects of aging on the ability to spell may help distinguish between alternate accounts of age-related declines in language production.

With such empirical, practical and theoretical considerations in mind, we first review available data on how aging affects spoken word retrieval, and then outline theoretical issues associated with effects of aging on spoken language production. We next review general theories and empirical research on the representation of orthographic knowledge, and develop a new theory that makes detailed predictions regarding effects of aging on retrieval of orthographic knowledge. We then discuss the variables and other procedural details adopted in the present experiment for testing those predictions.

Empirical Effects of Aging on Spoken Word Retrieval

Older adults are slower and less accurate than young adults in saying a word that corresponds to a definition (e.g., Bowles & Poon, 1985), starts with a specified letter or falls into a specified category (e.g., McCrae et al, 1987). Older adults also are slower (Thomas et al., 1977) and less accurate than young adults at naming pictures of familiar objects and actions (e.g., Albert et al., 1988; Au et al., 1995; Bowles et al., 1989; Mitchell, 1989; Nicholas et al., 1985, 1997; but see Poon & Fozard, 1978). Tip-of-the-tongue phenomena (TOTs), where speakers can retrieve the meaning of a low frequency word that they know they know, but cannot produce the word because they are unable to retrieve its full phonology, also increase with age, both in everyday life and in laboratory settings (Burke et al., 1991; Maylor, 1990; Rastle & Burke, 1996). Finally, older adults produce words more slowly than young adults at maximum rate, and take longer than young adults to begin to say a visually presented word (Balota & Duchek, 1988; Liss et al., 1990).

Two aspects of this pattern of age-linked declines in spoken word retrieval are remarkable. One is that these declines do not reflect across-the-board declines in language processes because processing within the semantic system exhibits age-constancy (see e.g., MacKay & Burke, 1990). The other is that these declines involve retrieval of familiar information (so called crystallized intelligence; Christensen, 1998), and cannot be explained in terms of well-known deficits in the ability to encode new information (so called fluid intelligence; Christensen, 1998). If spelling retrieval exhibits similar declines in college-educated older adults, then this remarkable pattern would extend to the corresponding level of writing, another highly practiced language production skill.

However, we note at the outset that age-linked spelling deficits are unlikely: According to a recent review of research on semantic memory and aging (Bowles, 1993, p. 304), age differences do not occur “in the ability to access the internal representation of a word in semantic memory when the stimulus provides the orthography or phonology of the target word.” Because the stimulus provides the target phonology when people are asked to spell auditorily presented words, aging should not affect correct spelling if Bowles’ account is correct. Aging should likewise have little effect on spelling under the still prevalent view that crystallized intelligence, and in particular, verbal skills, show little or no decline in old age (Botwinick, 1984, pp. 255-271; Christensen, 1998).

Aging and Retrieval of Phonology: Theoretical Issues

To date, theories of age-linked declines in spoken word retrieval have focused mainly on questions of locus: Are the declines attributable to one cognitive system more so than to others? For example, are age-linked declines in picture naming attributable to the system for perceiving the pictures or to the system for producing names, or to both systems? And if the system for producing names is involved, are the declines attributable to the production of phonology or to the production of semantics, or to both? Thus, one account of age-linked declines on the Boston Naming test (BNT) postulates age-linked “difficulties with perceptual and semantic processing” (Au et al., 1995, p. 310). Another account interprets age-linked increments in time to retrieve familiar words as having a “system-universal” cause, i.e., a general slowing factor that applies across all cognitive systems, and not just perceptual or semantic systems or even language systems per se (see Burke & MacKay, 1997, for a recent review). A third account, the Transmission Deficit hypothesis of MacKay and Burke (1990), can be considered a hybrid account with both system-specific and system-universal aspects: The Transmission Deficit hypothesis postulates a universal factor, age-linked deficits in the transmission of priming across connections between nodes in a highly interconnected network, but the effects of transmission deficits vary depending on the detailed structure of the connections involved: Under the theory, connections differ in structure for perceptual versus production systems, and for phonological versus semantic units within the production system, so that age-linked declines on the BNT and on other language production tasks are mainly attributable to production rather than perceptual systems, and are mainly attributable to producing phonological rather than semantic units under the Transmission Deficit hypothesis. Because the Transmission Deficit hypothesis also predicts effects of aging on written language production that parallel those for spoken language production, we will examine the mechanisms of this theory in detail, first for spoken language production and subsequently for written language production.

The Transmission Deficit Hypothesis and Retrieval of Phonology

Under the Transmission Deficit hypothesis, connections between nodes, the hypothetical processing units in the Node Structure theory (NST) of MacKay (1987), transmit priming less efficiently as a function of three factors: aging, non-recent activation of the connected nodes, and infrequent activation over the course of a lifetime. Priming can be inhibitory or excitatory in nature and is transmitted simultaneously or in parallel across all active connections. Priming has two main functions. One is to allow the simultaneous integration of many different sources of information. The other is to prepare nodes for possible activation: Only the most primed node of a given type can be activated at any given point in time. Unlike priming, then, activation requires engagement of a special activating mechanism that follows a “most-primed-wins” activation principle. Also unlike priming, activation proceeds sequentially so that the units represented by nodes can be retrieved in proper order as well as at the proper time in speech, writing, typing, and spelling.

Nodes for producing spoken speech in NST are organized hierarchically into three systems: a general purpose semantic system representing the meanings of words, a phonological system representing syllables and segments or speech sounds, and a muscle movement system for moving, e.g., the jaw, tongue, and laryngeal structures for spoken speech. To illustrate this hierarchic organization, Figure 1 shows some of the connections that play a role in producing the word calendar at semantic and phonological levels. The highest level, lexical node representing calendar in the semantic system is connected top-down to three nodes representing the syllables /ka/ and /len/, and /dêr/ in the phonological system in Figure 1[1]. Syllable nodes are hierarchically connected top-down to nodes representing phonological compounds, e.g., /-en/ and /-êr/, and segments, e.g., /k-/, which map onto a hierarchically organized system of muscle movement nodes for spoken production of the word calendar. (See MacKay, 1987, pp. 36-38, for details of node structures within phonological and muscle movement systems). In error-free spoken production of the word calendar, then, the lexical node for calendar is activated first, followed by its first syllable node and the first segment node of its first syllable, before the muscle movement nodes for producing that initial segment can be activated and onset of movement can begin.

How do the hierarchic, top-down connections in Figure 1 bear on the Transmission Deficit hypothesis? Effects of a transmission deficit in the theory are likely to be greatest when a node critical to a task is rarely and non-recently activated, and receives priming from only a single source or connection within the network. The basis for this "single source condition" is that no other sources of priming will be able to offset the reduced priming across a critical connection receiving priming from a single source. This is precisely the case for priming delivered top-down to phonological nodes during spoken language production: Phonological nodes have only a single or critical top-down connection, and so receive a single source of priming without the possibility of convergence or summation of priming from other nodes to offset age-linked transmission deficits. For example, the node representing the syllable /ka/ in Figure 1 receives top-down priming from a single lexical node during spoken production of the word calendar[2]. This limitation in how many connections can deliver top-down priming to phonological nodes during spoken language explains why phonological but not semantic information is inaccessible in TOTs: The single source condition does not in general hold for units in the semantic system, where connections generally converge from many nodes onto one node. Consequently, many sources of priming can offset age-linked transmission deficits across any one connection between semantic units, unlike phonological units (see MacKay & Burke, 1990; also MacKay, Abrams, & Pedroza, 1998). The single source condition also explains why TOTs increase with aging, and why older adults in the TOT state take longer to resolve TOTs, access less phonological information about the target word, have fewer alternative words come persistently to mind, and experience disproportionately more TOTs for proper names than young adults (see Burke et al., 1991). The susceptibility of top-down phonological priming to transmission deficits also explains other age-linked difficulties in spoken word retrieval. For example, age differences in word retrieval decrease when orthographic and phonological cues are provided, but not when additional semantic cues are provided (Bowles & Poon, 1985), as if the age-linked declines affect retrieval of phonology more so than semantics. (For detailed Transmission Deficit accounts of these and a wide range of other aging effects, see MacKay & Burke, 1990).

Aging and Retrieval of Orthography: Research and Theory

Although many sophisticated empirical studies have examined orthographic processes “on the input side”, especially the time required to read visually presented words aloud (see e.g., Glushko, 1979; Jared, McRae, & Seidenberg, 1990), empirical research on spelling retrieval in educated adults is extremely limited, consisting largely of single case studies of spelling impairments in brain damaged patients (Badecker, Hillis, & Caramazza, 1990; Caramazza & Hillis, 1990; Hillis & Caramazza, 1990; Katz, 1991; Levine, Mani, & Calvanio, 1988; Neils, Boller, Gerdeman, & Cole, 1989; Posteraro, Zinelli, & Mazzucchi, 1988). We found only two empirical studies on spelling retrieval in normal young adults (Fisher, Shankweiler, & Liberman, 1985; and Wing & Baddeley, 1980), and no studies on spelling retrieval in healthy older adults.

Turning to theories, two contrasting classes of theories have been developed to explain the input-side orthographic processes that occur when normal young adults read a word aloud, but neither class of theories is currently capable of explaining all available data, even within this limited empirical range (see, e.g., Cortese & Simpson, 1996; and Rastle & Coltheart, 1996). One class, known as parallel distributed processing (PDP) theories, represents orthographic knowledge in terms of connection strengths or weights within a complex, highly interactive network involving large numbers of excitatory and inhibitory connections for each word, without rules of any kind for representing either regularly- or irregularly-spelled words (see e.g., Plaut, McClelland, Seidenberg, & Patterson, 1996). However, PDP theories of this type have had limited success in modeling the acquisition of spelling: Unlike humans, after more than 60 training trials with each of 1000 words (preselected to exclude homophones and words with phonemes not in one-to-one correspondence with letters), the PDP program of Olson and Caramazza (1994) could at best spell only 70% of the words correctly.

The second class of input-side theories has been labeled "the orthodox theoretical conception of the processes subserving spelling in English" (Barry, 1994, p. 33). These "dual route" theories (e.g., Coltheart, Curtis, Atkins & Haller, 1993) postulate a categorical distinction between regularly- versus irregularly-spelled words, such that a word is regularly-spelled if all of its speech sounds follow the most common orthography-to-pronunciation pattern in the lexicon, but is irregularly-spelled if it follows a unique or uncommon orthography-to-pronunciation pattern. For example, bunt, punt, and hunt are regularly-spelled in dual route theories because they follow the dominant orthography-to-pronunciation pattern in English, whereas bush and push are irregularly-spelled because they follow an uncommon orthography-to-pronunciation pattern.

In dual route theories, an “indirect” route from orthography-to-phonology-to-semantics incorporates “grapheme-to-phoneme correspondence rules” for translating orthography into phonology, and plays an essential role in pronouncing regularly-spelled words such as hunt. However, in the case of irregularly-spelled words such as bush, a “direct route” leads straight from orthography to semantics, bypassing phonology and the grapheme-to-phoneme correspondence rules. This “direct route” directly accesses the meaning of irregularly-spelled words, which in turn enables the speaker to pronounce these words.

In contrast to the many input-side theories devoted to the task of reading visually presented words aloud, there are no detailed output-side theories to explain how normal adults spell words letter by letter in self-generated typing, writing, or spoken spelling production, or in the task examined here, manually transcribing auditorily presented words. Detailed theories of how aging affects retrieval of orthographic knowledge are also nonexistent. Moreover, creating an output-side theory by “mirror imaging” an input-side theory of orthographic processing is impossible because instances of “regularity” differ on the input- versus the output-side: In general, input-side (orthography-to-phonology) relations are more regular or consistent than output-side (phonology-to-orthography) relations (see Barry, 1994). For example, STREET has only one possible pronunciation and is regular on the input side (the orthography-to-phonology direction), but STREET is irregular on the output side (the phonology-to-orthography direction) because /striyt/ could be spelled STREAT. We therefore had to develop an output-side theory of our own to guide the present research into effects of aging on the ability to spell auditorily presented words. The theory is a natural extension to orthographic retrieval of the Transmission Deficit hypothesis of MacKay and Burke (1990) and the NST account of phonological retrieval discussed earlier.

NST and the Retrieval of Orthography

Our first assumption is that “regular spelling” is a valid concept, but that it applies to “speech sounds in context”: That is, we define a speech sound as regularly-spelled if it follows the most common spelling pattern for that speech sound in that context for all words of that type in the lexicon, and we define a speech sound as irregularly-spelled if it follows a unique or uncommon spelling pattern. For example, the speech sound /ê/ in cooker is regularly-spelled because most nouns of that type, e.g., worker, baker, maker, follow the same spelling pattern, but /ê/ is irregularly-spelled in calendar because only a few other nouns, e.g., beggar, burglar, spell /-êr/ as [-AR]. However, only one speech sound in calendar is irregularly-spelled under NST: Its remaining seven speech sounds are regularly-spelled. This contrasts with dual route theories, where words are the unit of analysis, and calendar is simply an irregularly-spelled word.

To further illustrate the concept of “speech sounds in context” in NST, the speech sound /tŠ/ is usually spelled CH in initial positions, e.g., CHIP, CHURN (excluding non-English words such as Tschaikovsky) and after a comlex vowel, e.g., BIRCH, BLEACH (MacKay, 1987, p. 32). However, /tŠ/ is usually spelled TCH when it follows immediately after a short vowel as in CATCH and SCOTCH. A similar concept of “orthographic units in context” is necessary to represent “purely orthographic regularities” such as the rule [I] before [E] except after [C], to represent relations between orthographic units (as in doublets such as [-MM-] and [-SS-], and digraphs such as -CK, SH-, and CH-), and to represent relations between orthographic units, morphological units, and different types of phonological units (e.g., consonants, consonant clusters, vowels and vowel groups or rimes; see Treiman, 1993, 279-280; also Olson & Caramazza, 1994).

Like phonological nodes, orthographic nodes are part of a hierarchically organized network that originates in the general-purpose semantic system: The lexical node for a word is connected top-down to nodes in the orthographic system, which are connected top-down to nodes in the muscle movement systems for writing and typing. However, writing and typing are special because the orthographic system also receives non-hierarchic or lateral connections from the phonological system that determine the spelling for "regularly-spelled" letters in a word, and enable writers to generate a "regular spelling" for words that they have heard, but never previously seen spelled[2].

For spelling an irregularly-spelled component of a word, the orthographic system contains a "quasi-irregular node" that introduces the irregularly-spelled letter(s) and blocks the regular spelling pattern. By way of illustration, Figure 1 shows the quasi-irregular node and lateral connections for spelling the word calendar under NST. The highest level, lexical node representing calendar connects top-down to a node in the orthographic system that represents the fact that calendar belongs to a subset of quasi-irregular nouns that spell /ê/ as [A]. This quasi-irregular node is connected top-down via an inhibitory connection to the letter [E] and via an excitatory connection to the letter [A].

We turn now to the orthographic processes in NST for writing or typing irregularly spelled letters in auditorily presented words. These NST processes are general in nature, identical to those for phonology discussed earlier, and independent of the validity of the representational assumptions embodied in Figure 1. Under NST, complex priming interactions between the lexical node for the word, its phonological nodes, and its quasi-irregular node enable activation of the appropriate orthographic nodes for writing and typing irregularly spelled letters and letter clusters. For example, when writing the word calendar, the lexical node for calendar is activated first, which causes strong top-down priming of the phonological nodes for calendar and its quasi-irregular node in the orthographic system (see Figure 1). Activating this quasi-irregular node in turn delivers strong excitatory priming to the letter [A] and strong inhibitory priming to the letter [E] which counteracts the priming arriving from the lateral connections from the phonological system, prevents activation of the regular spelling pattern, and enables correct spelling of calendar as calendar (see Figure 1). This same quasi-irregular node also becomes activated when writing, typing, or spelling the small number of other nouns that spell /ê/ as [A], e.g., burglar, beggar, ergo the term quasi-irregular.

To summarize, the structure of orthographic knowledge in NST resembles dual-route theories in some abstract respects because quasi-irregular nodes represent a type of orthographic rule, and the top-down and lateral connections in NST can be viewed as multiple "routes", albeit simultaneous and "cooperative" routes rather than "either-or" routes. However, NST also differs from dual-route theories (e.g., Coltheart et al., 1993) in other respects, e.g., its rules are quasi-irregular rather than categorically irregular, unlike the phoneme-correspondence rules in dual-route theories. At the same time, NST resembles PDP theories (e.g., Plaut et al., 1996) in some abstract respects, e.g., connection strengths or weights are a major factor in NST, but differs from PDP theories in other respects, e.g., connection weights are not the only factor in NST; how connections are structured is an equally important factor that enables representation of quasi-irregular rules.

Effects of Aging on Orthographic Retrieval in NST

We now examine effects of age-linked transmission deficits on orthographic retrieval in NST. Transmission deficits in connections resembling those in Figure 1 predict that older adults will be especially likely to misspell irregularly-spelled aspects of English words because nodes critical to this task satisfy the single source condition: They receive priming from only a single source or connection within the network. For example, the quasi-irregular node for calendar in Figure 1 can only receive top-down priming from its one connection with the lexical node for calendar. Consequently, deficits in transmission of priming across that one connection will reduce the likelihood of activating that quasi-irregular node. This can have two possible consequences. One is that the wrong quasi-irregular node becomes activated: Because only the most-primed quasi-irregular node can be activated at any point in time, the wrong quasi-irregular node may be activated in error if a transmission deficit prevents the appropriate quasi-irregular node from achieving most-primed status. In short, older adults will sometimes apply the wrong quasi-irregular pattern when misspelling irregularly-spelled words.

The second possible consequence is that no quasi-irregular node achieves enough priming to become activated, and the regular spelling pattern predominates. For example, if no quasi-irregular node is activated in spelling the word calendar, the letter [E] will not be inhibited, and the letter [A] will not be activated, and calendar will be misspelled calender, following the pattern represented by the lateral connections for spelling most English words. This possibility suggests that in absolute numbers, misspellings of older adults will tend to have the same pronunciation as the original word under the Transmission Deficit hypothesis.

NST also predicts that misspellings due to age-linked transmission deficits will be less likely in absolute numbers for the regularly- than irregularly-spelled aspects of words. The lateral, phonology-to-orthography connections for spelling regularly-spelled letters are used with extremely high frequency over the course of a lifetime, a factor that will tend to offset transmission deficits. By comparison, irregularly-spelled components receive relatively little practice because they occur in only a few words, and these words generally contain more regularly- than irregularly-spelled components, as the calendar example illustrates. Thus, the lateral connection for spelling /r/ as [R] may be activated many times a day when typing, writing or spelling the many English words that contain one or more regularly-spelled /r/s. By contrast, the single connection linking calendar to its quasi-irregular node is unique to the word calendar (see Figure 1), and only transmits priming when writing, typing, or spelling the word calendar. Similarly, the single connection linking this quasi-irregular node to [A] (see Figure 1) is only activated when writing, typing, or spelling the small number of words that spell /ê/ as [A], e.g., burglar, beggar. Moreover, age will multiply the frequency difference between regularly- versus irregularly-spelled letters: Over the longer lifetimes of older adults, nodes for regularly-spelled letters will be activated much more often than nodes for irregularly-spelled letters. Because this age-linked difference in frequency of activation will tend to offset age-linked transmission deficits, the Transmission Deficit hypothesis predicts that older adults will exhibit little or no deficit in spelling regularly-spelled letters.

Nonetheless, the lateral connections that link phonological nodes to the orthographic nodes for representing regular spelling constitute a single source of priming that should eventually succumb to age-linked transmission deficits under the Transmission Deficit hypothesis (see Figure 1), so that very old adults should exhibit a deficit in spelling regularly- as well as irregularly-spelled aspects of words. However, transmission deficits in lateral connections can also exhibit paradoxical effects under NST. For example, a deficit in transmission of priming across the connection from to /-ê/ to [E] in Figure 1 will reduce the priming delivered to the letter [E], but this will increase the probability that calendar will be correctly spelled as calendar rather than misspelled as calender.

To summarize, NST makes many predictions that are counterintuitive within the context of current research (see Bowles, 1993; Christensen, 1998). Age-linked transmission deficits predict that misspellings will increase as a function of aging, and that older adults will be especially likely to make errors on irregularly- than regularly-spelled parts of a word because age will multiply the frequency differences between irregularly- vs. regularly-spelled components. Similarly, misspellings of older adults involving irregularly-spelled components will in general be especially likely to have the same pronunciation as the original word because age will multiply the frequency differences between same- versus different-pronunciation components. However, very old adults will also exhibit an age-linked increase in absolute number of errors on regularly-spelled parts of a word under NST.

NST also predicts that more low than high frequency words will be misspelled by both young and older adults because word frequency covaries with recency and frequency of node activation, two factors that offset transmission deficits (see e.g., Burke et al., 1991). However, errors on both high and low frequency words will tend to involve irregularly-spelled letters more often than regularly-spelled letters due to the differing frequencies of these components. Moreover, for both young and older adults, misspellings of irregularly- and regularly-spelled letters will in general have the same pronunciation as the original word due to the greater frequency of same-pronunciation components.

To test these predictions, we presented a tape recorded series of difficult-to-spell English words to young and older participants, who simply wrote the words down at their own pace, with instructions that encouraged accurate spelling. The instructions also de-emphasized response speed to rule out possible explanations based on general slowing and age-linked interactions between speed and accuracy (see e.g., Balota & Ferraro, 1993). In addition, the words were repeated and articulated clearly at a relatively slow rate; participants could stop and restart the tape recorder as often as desired if they needed more time; and perceptual errors were factored out in our analyses to rule out age-linked sensory or perceptual deficits as determinants of our results. To test the prediction that low frequency words will be misspelled more often than high frequency words, half of our stimuli were high frequency, e.g., rhythm, spontaneous, and half were low frequency, e.g., chauffeur, pageant.

Method

Participants

The 85 participants fell into three groups, labeled young, older, and oldest adults, with means and standard deviations (SD) for standard background characteristics shown in Table 1. The 35 young adults (15 males; 20 females) were 17-23 years old and participated in return for partial course credit from introductory UCLA psychology classes. The 25 older adults (10 males; 15 females) were 60-71 years old, and the 25 oldest adults (9 males; 16 females) were 73-88 years old. Older and oldest adults lived at their homes in greater Los Angeles, received $10 plus travel expenses as members of the UCLA Cognition and Aging Lab pool (current N=198), and were recruited from the UCLA Alumni Association, senior citizen centers, and churches. All participants were native speakers of English and reported normal hearing, with no neurologic or serious medical problems. The three groups differed reliably in years of education, $F(2,81)=31.68$, $p<.0001$; and Nelson-Denny vocabulary scores, $F(2,79)=26.25$, $p<.0001$. The older adults had greater education and higher Nelson-Denny scores than the oldest adults, who had greater education and higher Nelson-Denny scores than the young adults (see Table 1; all post hoc differences $p<.05$ via Bonferroni tests).

Materials

Materials consisted of 40 words shown in Table 2, plus 6 practice words of comparable length, frequency, and spelling difficulty. All were listed as difficult to spell in Baron, Treiman, Wilf, & Kellman (1980) or in Norback (1974), and none were recognizably foreign, e.g., Tschaikovsky. Most were common nouns (N=21), with some adjectives (N=10), some verbs (N=4), and at least one noun-verb (endeavor). Based on Francis and Kucera (1982; see Table 2), 20 experimental words were high frequency (mean 31.3 per million; e.g., committee), and 20 were low frequency (mean 2.2 per million; e.g., inoculate). High and low frequency words were equally long (median length, 9 letters), and equally often ended in familiar suffixes, e.g., -ment, -er. A male experimenter recorded the words slowly and distinctly in standard American dialect on a Tascam Porta 8-track tape deck linked to Realistic Nova 55 headphones. Order of the words on the tape was randomized across five different versions of the experiment, with versions assigned to participants in each group by order of arrival.

Procedure

All participants first answered a metamemory questionnaire concerning their spelling ability and activities with possible relations to spelling. The questionnaire asked how many hours per week participants spent reading, writing, and solving crossword puzzles, and asked participants to rate how rigorously their grade school taught spelling skills on a ten point scale (1 = lax, 10 = rigorous), and to rate their current spelling ability on a five point scale (1 = poor, 5 = excellent). Questionnaires for the older and oldest adults also contained an additional five point scale for rating their remembered spelling ability at age 20.

All participants then heard the stimulus words over headphones with instructions to print each word legibly on a numbered response sheet, guessing at the spelling if necessary. A “trial” consisted of a stimulus number, a 425ms warning tone, a 3s pause, then the stimulus word, a 10s pause, and a repetition of the stimulus word. Next came a 20s pause during which participants printed the word next to its stimulus number on the response sheet. If participants needed more time to respond, they could press the “pause” button to stop the tape recorder, and press “play” to restart. During practice trials, participants were encouraged to adjust the volume of the tape recorder to whatever level was comfortable for them. After the practice trials, the experimenter answered questions, and then left the room. At the end of the experiment, the experimenter checked responses for legibility in order to create a more legible copy if necessary.

Results

We used three criteria to score mishearings: if participants spelled an English word other than the word on the tape (most frequent); if participants spelled a nonword that three judges agreed must have been a mishearing, e.g., voraclly instead of broccoli; and if participants gave no written response (least frequent). By these criteria, mishearings occurred on 4.4% of the trials, and as might be expected, increased systematically with aging: young, 1.7%; older, 3.4%; and oldest, 9.1%, a reliable age effect, $F(2,82) = 8.29$, $p < .0005$. Post-hoc Bonferroni tests indicated that mishearings were reliably more common ($p< .05$) for the oldest than for either the young or the older participants, who did not differ reliably from each other. Unless noted otherwise, we excluded mishearings from all further analyses,[3] which are organized under the headings Main and Subsidiary Results.

Main Results

Main Results fall into three sections: Percent correct spelling of high versus low frequency words; correlations with background characteristics and questionaire responses; and errors on regularly- versus irregularly-spelled letters in high frequency words. The dependent measure was whole words in the first two sections, but errors per letter in the third section.

Percent Correct Spelling of High versus Low Frequency Words

Mean percent correct spelling per participant for the three age groups appears as a function of word frequency in Table 3, together with SD and overall percent correct. A 3 (age) x 2 (frequency) multivariate analysis of variance (MANOVA) applied to these data indicated no main effect of age, $F(2,82)=2.68$, $MSe=.08$, $p>.073$, but a main effect of frequency, $F(2, 82)=86.22$, $MSe=.01$, $p<.001$, and an age x frequency interaction, $F(2, 82)=5.66$, $MSe=.01$, $p<.005$. Subsequent analyses indicated no age effect for low frequency words, $F(2, 82)=1.52$, $MSe=.04$, $p>.224$, but a reliable age effect for high frequency words, $F(2, 82)=4.04$, $MSe=.05$, $p<.021$. Post hoc Bonferroni tests on this age effect for high frequency words indicated no reliable difference between the older and oldest groups, but reliably better spelling for the young adults than the oldest adults ($p<.05$).

Why did the oldest adults exhibit a spelling deficit for high frequency words relative to young adults, but not for low frequency words? This pattern is important to understand because similar age x word frequency interactions have been reported in other studies (e.g., Allen, Madden & Slane, 1995;

Stadtlander, 1995). Age-linked differences in familiarity provide one possible explanation. Under this "familiarity hypothesis", the young adults had not encountered (i.e., did not know) many of the low frequency words, and therefore did not know how to spell them, unlike the older and oldest adults, who had encountered these words many times over the course of their (longer) lives. However, high frequency words were equally familiar to both groups, so that the oldest adults made more errors than the young adults on high frequency words because of a decline in their ability to spell familiar words that they once knew how to spell correctly.

Support for this familiarity hypothesis came from several sources. One was the raw frequency with which young adults made same-pronunciation errors on low frequency words. Same-pronunciation errors, sometimes called regularizations and "legal misspellings" (Treiman, 1993, pp. 23-51), are misspellings that can be pronounced in the same way as the correctly spelled word because they follow the phonology-to-orthography pattern in many other words. For example, 97% of English words spell /i/ as [I], e.g., fist, and only 3% spell /i/ as [Y] as in cyst (Barry, 1994). Consequently, cist instead of cyst is a same-pronunciation misspelling, and so are spontanious, pagent, and generocity. Different-pronunciation errors are misspellings that cannot be pronounced in the same way as the original word because their phonology-to-orthography pattern is rare, e.g., fyst (for fist; by analogy with cyst), or found in no other word, e.g., decsendant (for descendant), concesus (for conscious), and sasuage for (sausage).

Table 4 shows the raw frequency of same- versus different-pronunciation misspellings per participant as a function of word frequency for the three age groups, together with SD and overall errors. The raw frequency of same-pronunciation errors increased with aging for low and high frequency words, and so did different-pronunciation errors involving high frequency words (see Table 4). However, for low frequency words, young adults made more same-pronunciation errors than did the older and oldest adults, a pattern confirmed by a 2 (frequency) x 2 (error type) x 3 (age) MANOVA. The frequency x age x error type interaction was reliable in this analysis, $F(2,82)=4.09$, $MSe=3.20$, $p<.02$, with an age x frequency interaction only reliable for same-pronunciation errors, $F(2,82)=5.59$, $MSe=3.55$, $p<.005$, and with a frequency x error type interaction only reliable for young adults, $F(2,82)=9.74$, $MSe=3.20$, $p<.002$. This pattern suggests that young adults were unfamiliar with many of the low frequency words, and reverted to "spelling by sound," the default strategy for spelling unknown words. Because very few of our stimuli contained only regularly-spelled letters (see Table 2), this strategy would cause young adults to make large numbers of same-pronunciation errors on low frequency words.

A second source of support for the familiarity hypothesis came from a multivariate analyses of covariance (MANCOVA)[4] using Nelson-Denny scores as covariate, an analysis that should more closely equate relative familiarity of the low frequency words across our age groups. Consistent with the familiarity hypothesis, the MANCOVA indicated a significant regression of Nelson-Denny scores on percent correct spelling, $F(1,78)=24.69$, $MSe=.06$, $p < .001$. The estimated or adjusted mean percent correct spelling per participant with Nelson-Denny scores as covariate is shown in Figure 2 (left panel), and a 2 (word frequency) x 3 (age) MANCOVA on these data indicated an age x frequency interaction, $F(2,79)=5.13$, $MSe=.01$, $p < .008$, with greater age differences for high than low frequency words (see Figure 2), together with main effects of frequency, $F(1,79)=79.25$, $MSe=.01$, $p < .001$, and of age, $F(2,78)=9.92$, $MSe=.06$, $p < .001$. Post hoc tests showed that the age effect was reliable for high frequency words, $F(2,78)=11.46$, $MSe=.04$, $p < .001$, with greater correct spelling for the young than the oldest adults, $p < .001$, and for the young than the older adults, $p < .001$, but no difference in correct spelling for the older and oldest adults, $p > .525$. The age effect was also reliable for low frequency words, $F(2,78)=6.33$, $MSe=.03$, $p < .003$, with greater correct spelling for the young than the oldest adults, $p < .001$, and for the young than the older adults, $p < .009$, but correct spelling for the older and oldest adults did not differ, $p > .568$. These findings indicate that high frequency words were correctly spelled more often than low frequency words, and that the older and oldest adults in our sample exhibited a decline in spelling ability relative to young adults for both high and low frequency words when differences in vocabulary are factored out, but this decline was relatively greater for high than low frequency words.

We also conducted covariate comparisons of same- versus different-pronunciation errors in the present data. Figure 2 (right panel) shows the adjusted mean number of same-pronunciation and different-pronunciation errors per participant as a function of word frequency for the three groups, with Nelson-Denny scores as covariate. A 3(age) x 2(frequency) x 2(error type) MANCOVA on these covariate data revealed a main effect of age, $F(2,78)=5.95$, $MSe=10.37$, $p < .004$, and a main effect of error type, $F(1,79) = 234.43$, $MSe=5.41$, $p < .001$, with more same- than different-pronunciation errors (see Figure 2). The main effect of frequency was also reliable, $F(1,79) = 54.56$, $MSe=1.46$, $p < .001$, with more errors on low than high frequency words. The error type x age interaction and error type x frequency interaction were not significant, $F < 1$, but there was a significant age x frequency interaction, $F(2,79)=4.38$, $MSe=1.46$, $p < .016$, that was mediated by an age x frequency x error type interaction, $F(2,79)=3.61$, $MSe=3.49$, $p < .031$. Further analysis of this three-way interaction showed that the older and oldest adults made more same-pronunciation errors than young adults for high frequency words, and more different-pronunciation errors for both high and low frequency words (largest $p < .007$), but there were no age differences in number of same-pronunciation errors for low frequency words ($p > .943$).

To summarize, our MANCOVAs tended to equate relative familiarity of low frequency words across age groups (compare Table 3 with Figure 2), but may not have been entirely successful because the young adults continued to make a disproportionate number of same-pronunciation errors in spelling low frequency words. However, the trend suggests that relative to the older and oldest adults, young adults would make reliably fewer same-pronunciation errors on low frequency words with a more successful procedure for equating familiarity.[5]

Correlations with Background Characteristics and Questionnaire Responses

Mean hours per week spent reading, writing, and doing crossword puzzles are shown for the three age groups in Table 1, together with SD. Also shown in Table 1 are mean ratings of current spelling ability for the three groups, the rigor with which their grade school taught spelling skills, and for the older and oldest adults, their spelling ability at age 20. To determine whether participants could accurately evaluate their current spelling ability, we correlated self-ratings of current spelling ability with percent correct spelling in the main experiment. The correlations were highly reliable within each age group (smallest $r=.65$, largest $p < .023$) and across all three age groups, $r(47)=.66$, $p < .001$, suggesting that self-ratings of current spelling ability provided a reasonably accurate estimate of actual spelling ability. Although we had no comparable test of validity for self-ratings of spelling ability at age 20 for the older and oldest adults, we nonetheless were able to test whether the older and oldest adults were aware of a decline in their ability to spell by comparing self-ratings of spelling ability that they provided for age 20 and for their current age. Ratings were lower for current than former spelling ability for both the older and oldest adults (see Table 1), but the difference was only reliable for the oldest adults, $t(17) = -2.20$, $SE = .202$, $p < .042$. These findings suggest that the oldest but not the older adults were aware of a decline in their spelling skills.

To determine what other age-linked factors in the present study might be related to spelling ability, we compared estimates for the three groups of hours/week spent reading, writing, solving crossword puzzles, and of how rigorously their grade school taught spelling skills. The three groups differed at $p<.05$ for only one of these reported attributes: hours spent writing per day, $F(2,38)=8.31$, $p<.001$. Post hoc Bonferroni tests indicated no reliable difference between the older and oldest adults at $p<.05$, but young adults reported reliably more hours per day writing (M = 3.75hrs.) than either the older adults (M = 1.67 hrs.) or the oldest adults (M = 1.00 hrs.). This difference in estimated time spent writing makes sense in view of the ongoing educational activities of the young adults, but correlations between percent correct spelling and time spent writing were unreliable with $p>.05$ for all three age groups, which makes it unlikely that young adults correctly spelled high frequency words more often than the oldest adults due to the reliably greater time that they spent writing.

For young adults, percent correct spelling correlated reliably with no other background or questionnaire information at $p<.05$ (see Table 1), while for the older and oldest adults, the following and only the following characteristics correlated with percent correct spelling at $p<.05$: forward digit span for the older, $r(25)=.584$, and oldest adults, $r(23)=.651$; hours spent doing crossword puzzles for older adults, $r(15)=.539$; health rating for older adults, $r(25)=.436$; backward digit span for older adults, $r(25)=.558$; Nelson-Denny vocabulary scores for the older, $r(25)=.514$, and oldest adults, $r(23)=.740$; rigorousness of grade school teaching of spelling for oldest adults, $r(13)=.788$; and years of education for the oldest adults, $r(24)=.428$. These positive correlations with vocabulary scores and education highlight the remarkable nature of the decline in correct spelling of the oldest adults in our initial MANOVAs: Despite their greater education, higher vocabulary scores, and more frequent encounters with high frequency words over the course of their lifetimes, the oldest adults correctly spelled high frequency words reliably less often than young adults.

<u>Errors on Regularly- versus Irregularly-spelled Letters in High Frequency Words</u>

Because of the possible confound of age and familiarity with low frequency words discussed earlier, we confined our by-letter analyses to high frequency words. Two judges first labeled each letter in the high frequency words as either regularly-spelled or irregularly-spelled.[6] For example, regularly-spelled letters are capitalized in DEscENDANT, and irregularly-spelled letters are in lower case. The judges next determined whether spelling errors in the data involved regularly- or irregularly-spelled letters in the words. For example, the misspelling, decsendant, involves the irregularly-spelled letters in descendant, whereas the misspelling, descendent, involves a regularly-spelled letter. Other examples were more complex in nature. For instance, desendent contains two misspellings, one involving a regularly-spelled letter, and the other involving an irregularly-spelled letter. Finally, three judges determined whether misspellings of regularly- and irregularly-spelled letters had the same pronunciation as the original word or different pronunciation from the original word. For example, the misspelling decsendant is a different-pronunciation error because it cannot be pronounced the same as descendant. However, the misspelling descendent can be pronounced the same as descendant and is a same-pronunciation error.

Probability of errors was the dependent measure in our by-letter analyses because different stimulus words contained differing numbers of regularly versus irregularly-spelled letters. To obtain these probabilities we divided the number of errors per participant (summating multiple misspellings within the same word) on regularly- versus irregularly-spelled letters by the total number of letters of each type in the stimulus words. These probabilities are therefore a direct function of raw frequency rather than proportions of same- versus different-pronunciation errors.

Figure 3 shows the mean probability of same- and different-pronunciation errors per regularly-spelled letter (left ordinate) and per irregularly-spelled letter (right ordinate: Note expanded scale) for participants in the three age groups. A 3(age) x 2(component: regular versus irregular) x 2(pronunciation: same versus different from the original word) MANOVA on these data indicated that all three main effects were significant: age, $F(2,82)=4.34$, $MSe=.01$, $p < .016$, such that the oldest adults made more errors than the young adults; pronunciation, $F(1,82)=127.28$, $MSe=.01$, $p < .001$, such same-pronunciation errors were more frequent than different-pronunciation errors; and component, $F(1,82)=77.13$, $MSe=.01$, $p < .001$, such that more errors involved irregularly- than regularly-spelled letters in the words.

In addition, all of the two-way interactions were reliable at $p<.05$, except for one that was reliable at $p<.059$. However, these two-way interactions were mediated by an age x component x pronunciation interaction, $F(2,82)=7.28$, $MSe=.01$, $p < .001$, and further analyses of this three-way interaction indicated a significant age x pronunciation interaction only for irregular components, $F(2,82)=7.16$, $MSe=.01$, $p < .001$, such that the oldest participants made more same-pronunciation errors than the young participants on irregular components, but different pronunciation errors on irregular components did not differ as a function of age. However, the oldest participants made more same- and different-pronunciation errors on regularly-spelled letters than young and older participants, $p < .018$, with no difference between these latter groups, $p > .809$ (see Figure 3).

To summarize, the pattern of errors with letters and words as dependent measures was similar except for two new age-linked effects at the letter level. First, for irregularly-spelled letters, the oldest adults produced more same-pronunciation misspellings than the young adults, but different-pronunciation misspellings involving irregularly-spelled letters did not differ as a function of age[7]. Second, for regularly-spelled letters, both same-pronunciation and different-pronunciation misspellings were more common for the oldest adults than for the young and older adults. These results refine our findings with words as dependent measure, where same- and different-pronunciation misspellings of high frequency words did not differ reliably for the oldest and older adults (see Figure 2).

As predicted under NST, many of the different-pronunciation errors could be described as reflecting misactivation of a quasi-irregularity node, or misapplication of an inappropriate quasi-irregularity rule. For example, the doubled [R] in the misspelling of unecessary as unescerry can be described as a misapplication of the doubling rule that should apply to [S] in this word. Similarly, when assessment was misspelled assecement, the replacement of [SS] with [C] can be described as a misactivation of the quasi-irregularity node for spelling /s/ as [C] in proceed, recede, and concede. When picnicking was misspelled piquniquing, replacements of [C] and [CK] with [QU] can be described as misactivations of the quasi-irregularity node for spelling /k/ as [QU] in words such as piqued. Finally, the misspelling of grievance as greivance can be described as a misactivation of the quasi-irregularity node for spelling /E/ as [EI] in receive and conceive.

Subsidiary Results

Some aspects of our data neither contradicted the NST of orthographic retrieval nor constituted direct predictions of NST in its current state of development. However, these Subsidiary Results seemed noteworthy as a stimulus to further research and theoretical development, and we report them here with minimal speculation or theoretical comment in three sections entitled Proportions of same- versus different-pronunciation errors, Different-pronunciation errors of unknown origin, and Error detection and correction: The crossout data.

Proportions of Same- versus Different Pronunciation Errors

Unlike previous analyses testing NST predictions for raw frequencies, this section analyzed proportions of same- versus different-pronunciation errors. Our statistical analyses focussed on different- rather than same-pronunciation proportions (optionally because of the linear dependence or mirror-image relation between proportions of same- and different-pronunciation errors). These analyses revealed two empirical regularities discussed next.

The Different-Pronunciation Proportion Increases with Aging. As can be seen in Table 5A, the proportion of different-pronunciation misspellings per participant increased montonically with aging for both high and low frequency words. A 3(age) x 2(frequency) MANOVA on these data yielded a main effect of age, $F(2,77)=4.12$, $MSe=.04$, $p < .02$, with 5 older participants excluded because they made no errors on high-frequency words. Post hoc tests on this age effect indicated that the young adults had a reliably lower proportion of different-pronunciation misspellings than the oldest adults, $p < .009$, and a marginally lower proportion than the older adults, $p < .051$, with no difference between the older and oldest groups, $p > .63$. There was no age x frequency interaction, $F<1$, and the main effect of frequency was marginally significant, $F(1,77)=3.75$, $MSe=.02$, $p < .056$, with a lower proportion of different-pronunciation errors on high- than low-frequency words.

This main effect of age became statistically stronger in analyses with Nelson-Denny scores as covariate, despite the additional exclusion of one young and two oldest participants because of missing Nelson-Denny scores (see footnote 4). Table 5B shows the adjusted mean proportion of different-pronunciation misspellings for the three age groups with Nelson-Denny scores as covariate, and a 3(age) x 2(word frequency) MANCOVA on the different-pronunciation proportions yielded a main effect of age, $F(1,73)=7.26$, $MSe=.03$, $p < .001$, with a reliably lower proportion of different-pronunciation misspellings for the young than either the older or oldest participants ($p < .002$), who did not differ from each other ($p > .665$). However, the main effect of frequency became marginal in the MANCOVA, $F(1,74)=3.48$, $MSe=.02$, $p < .066$, with no age x frequency interaction, $F<1$.

Irregularly-Spelled Letters Increase the Different-Pronunciation Proportion. The mean proportions of same- versus different-pronunciation misspellings on regularly- versus irregularly-spelled letters in high frequency words are shown in Table 6 for the three age groups. A 3(age) x 2(component: regularly- vs. irregularly-spelled letters) MANOVA on the different-pronunciation proportions yielded only a reliable effect of component, $F(1,82)=23.16$, $MSe=.01$, $p < .001$, with a higher proportion of different-pronunciation errors on irregularly- than regularly-spelled letters. There was no main effect of age, $F(2,82)=1.09$, $MSe=.01$, $p > .34$, and no age x component interaction, $F(2,82)=1.93$, $MSe=.01$, $p > .15$.

Different-pronunciation Errors of Unknown Origin

Some different-pronunciation errors of our older and oldest adults were both remarkable and unexpected under our theoretical framework. These "different-pronunciation errors of unknown origin" became apparent in our letter-level analyses and involved addition, substitution, transposition, or omission of letters in ways that seemed less related to retrieval of quasi-irregular English spelling patterns than to "slips of the pen" reflecting transient inattention during writing (see MacKay, 1993). For example, when grievance was misspelled grievenance, the added [EN] was of unknown origin, but may reflect a false start that the participant failed to cross out in the written output. That is, the person may have begun to spell grievance as grievence, realized that [EN] should be [AN], but forgot to cross out [EN] after writing grievenance. An example of letter substitution is revervor for reservoir, as if [V] replaced [S] in anticipation of the upcoming [V] in reservoir. Transpositions involved correctly retrieved letters, but in transposed position within the word, e.g., delimma for dilemma. Examples of letter omissions are pinicking for picnicking, and assement for assessment. Other "errors of unknown origin" were more complex or ambiguous as to which letters were omitted, added, substituted, or transposed. An example is delimia for dilemma. Perhaps the [I] and [E] in dilemma were transposed during writing and a second [I] was substituted in error for the second [M]. Or perhaps the participant began to spell dilemma as delim-, realized that [I] was somehow in error, but carried through with delimia on the mistaken assumption that an [I] should be added.

Error Detection and Correction: The Crossout Data

If some misspellings in our data reflect "slips of the pen" by people who actually knew the correct spelling, then failure to detect and correct these errors may have contributed to our age-linked increase in misspellings: The older and oldest adults may have monitored their written output less carefully, or were less able to detect and correct their errors than young adults when inspecting their written output. As an initial test of this monitoring hypothesis, we examined how often participants crossed out and corrected their initial spelling of words in the original transcripts. These crossouts were readily scored because most participants wrote with a pen, and the erasures and crossouts by the three participants who wrote with a pencil were easy to discern.

Table 7 shows the percent correct spelling per participant as a function of age group for responses containing versus not containing a crossout. Contrary to the hypothesis that older adults monitored, detected, or corrected their errors less often than young adults, a 3(age) x 2(response type: crossed out versus not crossed out) MANOVA on these data indicated no main effect of age, $F(2,80)=2.05$, $MSe=.09$, $p > .134$, and no age x response type interaction, $F< 1$. However, there was a main effect of response type, $F(1,80)=41.65$, $MSe=.04$, $p < .001$, such that responses containing a crossout were spelled correctly reliably less often than responses not containing a crossout (see Table 7). One possible account of this result is that participants more often crossed out their initial spellings for words that were especially difficult to spell, an effect that did not differ as a function of age.

Crossout frequency also did not vary with age for responses that we had labeled correctly-heard versus misheard. Table 8 shows the percent crossouts per participant as a function of age group for responses in the misheard versus correctly-heard categories. A 3(age) x 2(response type: misheard versus correctly-heard) MANOVA on these data indicated no main effect of age, $F<1$, or of response type, $F<1$, and no age x response type interaction, $F(2,48)=2.27$, $MSe=.04$, $p>.114$. In short, all three age groups crossed out and corrected misheard words no more often than correctly-heard words.

Discussion

In summary, our main results were as follows: With perceptual errors and differences in vocabulary factored out, the older and oldest adults made more spelling errors than young adults for both high and low frequency words. Whether this age-linked spelling deficit applies only to "difficult-to-spell words" such as those in the present study remains to be explored. However, responses to a metamemory questionnaire indicated that the oldest but not the older adults were aware of a general decline in their ability to spell. Results with letters in high frequency words as dependent measure indicated that for regularly-spelled letters, the oldest adults produced more same- and different-pronunciation misspellings than the young and older adults, but for irregularly-spelled letters, the oldest adults only produced more same-pronunciation misspellings than the young adults, with no age differences in different-pronunciation misspellings.

We first discuss some unlikely accounts of these results, and then a more plausible one.

Unlikely Accounts of Present Results

Why did the older and oldest adults make more spelling errors than young adults? Under one hypothesis, the older and oldest adults never learned how to spell the words in the present study due to cohort-related educational deficiencies. However, this possibility seems unlikely for three reasons: The older and oldest adults had higher levels of education than the young adults; there was no difference in the rated rigor with which the grade schools of young, older and oldest adults taught spelling skills; and the deficit for the older and oldest adults was greatest for high frequency words, the very words that educational programs are likely to emphasize.

Nonetheless, we cannot rule out all possible cohort effects without a longitudinal study of spelling retrieval, and we are currently conducting such a study. The Transmission Deficit hypothesis predicts longitudinal age effects on spelling resembling those in the present study and in the longitudinal study of Au et al. (1995), which ruled out cohort accounts of age-linked declines in spoken word retrieval on the BNT. Consistent with this Transmission Deficit prediction, present results already rule out four cohort-relevant factors with possible links to spelling ability: how many hours/week participants spent reading, writing, and solving crossword puzzles, and how rigorously their grade school taught spelling skills. Factors that correlated with cohort, e.g., hours/week spent writing, were unrelated to spelling ability, and factors that correlated with spelling ability, e.g., hours/week spent solving crossword puzzles, could not explain the present age effects. Likewise difficult to explain as a cohort effect are the metamemory data indicating that our oldest participants were aware of a decline in their spelling skills since age 20.

It also seems unlikely that present results are due to a general slowing factor[8], even one embedded within a connectionist architecture resembling NST: Words in the present study were spoken at a relatively slow rate, participants could stop and restart the tape recorder if they needed more time, and they wrote down the words at their own pace, with response speed de-emphasized in the instructions. It is also difficult to explain the present age effects via the processing-speed theory of Salthouse (1996): In processing-speed theory, general slowing degrades cognitive performance because the products of earlier processing are no longer available at the time when later processing requires those products. It is unclear what interdependent earlier and later processing products processing-speed theory might postulate for spelling retrieval, which virtually always runs off letter by letter from left to right in a word.

Age-linked difficulties with sensory and perceptual processing likewise cannot account for present results because perceptual errors were factored out in our analyses. Another unlikely account is that age-linked declines in the ability to spell reflect difficulties in error monitoring such that relative to young adults, older adults either check their written output less carefully for errors, or are less able to detect and correct the errors in their written output than young adults. Contrary to this hypothesis, young adults crossed out and corrected their spellings in our transcripts no more often than the older and oldest adults. In addition, MacKay et al. (1998) directly tested for effects of aging on the ability to detect spelling errors in visually presented words, and showed that older adults are able to detect misspellings at least as well as young adults.

More difficult to rule out is the hypothesis that older adults write and type difficult-to-spell words less often than young adults, and monitor their written and typed output less carefully than young adults in their everyday lives, so that greater time spans have elapsed since the older and oldest adults generated the correct spelling for the words in the present study. However, this recency hypothesis is inconsistent with the crossout data in Table 7 and with our low correlations between correct spelling and hours per week spent writing. The recency hypothesis also fails to explain the parallel age-linked declines in written and spoken word retrieval since it is unlikely that healthy older adults do not speak as much as young adults (see Burke et al., 1991).

Present results are also difficult to explain under an Inhibition Deficit hypothesis, even one embedded within a cognitive architecture resembling NST. If inhibitory but not excitatory connections exhibit age-linked impairment (e.g., Hasher, Stoltzfus, Zacks, & Rympa, 1991; Hasher & Zacks, 1988), then one might expect an age-linked increase in same-pronunciation errors due to inhibition failure (see the inhibitory link in Figure 1), but not also an age-linked increase in different-pronunciation errors, contrary to present data with both words and letters as dependent measures.

The NST Account of Present Results

The Transmission Deficit hypothesis embedded within the NST of orthographic retrieval provides a plausible account of present data with words as dependent measure. As predicted under the Transmission Deficit hypothesis, age-linked declines in retrieval of orthography resemble declines in retrieval of phonology in spoken language production (see e.g., Albert et al., 1988; Bowles et al., 1989; Bowles & Poon, 1985; Burke et al., 1991; Balota & Duchek, 1988; Cohen & Faulkner, 1986; Liss et al., 1990; McCrae et al., 1987; Maylor, 1990; Mitchell, 1989; Nicholas et al., 1985; for reviews, see Burke & MacKay, 1997; MacKay & Abrams, 1996; and MacKay & Burke, 1990).

It is interesting that declines in spelling retrieval become readily detectable around the same age when declines in spoken word retrieval became readily detectable in the BNT data of Nicholas et al. (1985) and Au et al. (1995). However, this correspondence may be fortuitous because a variety of factors that are undifferentiated in BNT data can play a role in detectable age of decline. With materials matched for familiarity, detectable age of decline will differ for production versus perception, for semantic versus orthographic and phonological units, and for high versus low frequency words under the Transmission Deficit hypothesis, and consistent with this point, Burke et al. (1991) reported an age-linked decline in retrieval of very low frequency words with 37 as detectable age of onset.

As predicted under the Transmission Deficit hypothesis, low frequency words were misspelled more often than high frequency words, and the older and oldest adults made more same-pronunciation errors than young adults for high frequency words, e.g., misspelling calendar as the regularly-spelled, calender. Also consistent with Transmission Deficit predictions, the older and oldest adults made more different-pronunciation errors than young adults in spelling both high and low frequency words.

We turn now to results with letters rather than words as dependent measure. As predicted under NST, the older and oldest adults were especially likely to make same-pronunciation errors relative to young adults, as if age has a multiplicative effect on the frequency differences between same- versus different-pronunciation components. Also as predicted under NST, the older and oldest adults were especially likely to misspell irregularly-spelled letters relative to young adults, with no difference in the probability of misspelling regularly-spelled letters for young and older adults. However, deficits in spelling regularly-spelled letters did appear in the very oldest adults, consistent with the hypothesis that even the frequently used lateral connections representing regular spelling constitute a single source of priming that eventually succumbs to age-linked transmission deficits. That is, regularly-spelled letters involve a one-to-one lateral connection in NST (see Figure 1), and one-to-one connections are especially susceptible to age-linked transmission deficits, but because these lateral phonology-to-orthography connections receive so much use, effects of transmission deficits in these extremely strong connections only became evident in the oldest adults.

Another letter-level finding was that the oldest adults were especially likely to make same-pronunciation misspellings on irregularly-spelled letters relative to young adults, consistent with the hypothesis noted in the introduction that the most likely outcome of transmission deficits in connections to or from quasi-irregular nodes is a same-pronunciation misspelling. The oldest adults also made more different-pronunciation errors than the young and older adults when spelling regularly-spelled letters, but these misspellings involve an additional process under NST, namely inappropriate activation of a quasi-irregular node. That is, for the oldest adults, transmission deficits may have reduced priming delivered to the appropriate nodes, so that an inappropriate quasi-irregular node inadvertently received most priming and became activated when the "most-primed-wins" activation mechanism was applied, giving rise to these different-pronunciation errors on regularly-spelled letters.

Despite these fits with NST, further research is needed to evaluate possible effects of contextual factors on the nature of different-pronunciation errors. For example, different-pronunciation errors may be reduced or eliminated in words that only contain regularly-spelled letters or in an experiment that only presents regularly-spelled words. Further research is also needed to understand "different-pronunciation errors of unknown origin" and to determine why different-pronunciation errors did not differ in frequency as a function of age for irregularly-spelled letters in high frequency words (see Figure 3). Further research using procedures that definitively equate word familiarity across age groups is also needed to test the hypothesis that young adults made a disproportionate number of same-pronunciation errors for low frequency words (see Figure 2) because of their lack of familiarity with those words. Finally, further research is needed to conclusively establish whether age-linked transmission deficits in the production of orthography reflect age per se, or non-recent activation of the nodes in question, or both. However, such theoretical issues should not obscure or divert attention away from the practical implications of present data: that age-linked declines in spelling ability are to be expected as part of normal cognitive aging, and that steps to evaluate the consequences of those declines and to recommend remedial procedures, e.g., use of computerized spell checkers whenever possible, are in order.

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Footnotes

1. To distinguish phonological from orthographic units, we place phonological units between slashes, e.g., /-êr/, and orthographic units between square brackets, e.g., [-ER], a generally accepted convention.

2. For regularly-spelled words, the orthographic system also projects lateral connections to the phonological system that enable us to read visually never previously encountered words aloud. These lateral orthography-to-phonology connections are controversial in detail (compare e.g., Coltheart et al., 1993, versus Plaut et al., 1996), irrelevant to the present task and discussed no further here.

3. We also dropped the word /indayt/ from all analyses because it turned out to have two viable spellings (indict and indite).

4. Three participants (one young, two oldest) were lost in our MANCOVAs because of missing Nelson-Denny scores.

5. MANCOVAs based on estimates of stimulus familiarity collected at the end of the experiment might seem like a problem-free means of equating relative familiarity across age groups, but isn't: Familiarity judgments are relatively more difficult for older adults because of their episodic memory deficits and longer life spans, and comparing these judgments across age groups may be problematic in view of available evidence indicating that young and older adults make these judgments in fundamentally different ways (Parkin & Walter, 1992). We thank an anonymous reviewer for suggesting an end-of-experiment test of word knowledge resembling the Nelson-Denny except restricted to the stimuli actually presented in the experiment.

6. We dropped the word rhythm in our by-letter analyses because our judges disagreed on which of its letters were regularly- versus irregularly-spelled. Interjudge reliability following interaction between the judges was 100% for the remaining words. We would nonetheless have preferred to define

regularity in terms of the relative frequency of a given spelling for a given context-dependent speech sound. However, no such "degree of regularity" norms currently exist.

7. The spelling retrieval data of MacKay et al. exhibited this same pattern, with an age x error type interaction ($p < .027$) due to more same-pronunciation errors for older than young adults.

8. This is of course not to say that older adults might not exhibit slower retrieval times than young adults or that errors are not more likely for quickly- than slowly-produced spelling responses. However, the crossout data in Table 7 suggest that age-linked speed-accuracy trade-offs are unlikely in present results.

Table 1: Mean Background Characteristics and Questionnaire Responses, together with Standard Deviations (SD) for the Three Age Groups.

	Young Adults		Older Adults		Oldest Adults	
	M	SD	M	SD	M	SD
Age*	19.00	1.55	67.20	3.01	77.04	4.47
Years of Education*	13.07	1.45	17.32	3.00	15.33	1.55
Health Rating	7.80	1.64	8.28	1.49	7.90	1.88
Nelson-Denny Vocabulary*	15.29	2.98	21.12	2.47	19.43	4.08
Digit recall - Forward	7.59	0.95	7.12	1.51	6.83	1.27
Digit recall – Backward	5.34	1.29	5.20	1.22	4.83	1.47
Rated Spelling Ability at Age 20	N/A	N/A	3.35	1.27	3.42	0.81
Rated Spelling at Current Age	3.67	0.78	3.47	1.42	3.86	1.05
Reading (hrs/week)	4.50	2.81	3.33	1.88	3.14	1.10
Writing (hrs/week)*	3.75	2.60	1.67	1.72	1.00	0.55
Crossword Puzzles (hrs/week)	0.25	0.45	0.60	0.74	0.21	0.58
Rigor of Spelling Training	7.17	1.11	6.00	3.40	5.38	2.10

*Differences between age groups significant at $p < .001$ or less

Table 2: Frequency (per million) of High versus Low Frequency Stimuli (ordered by length)

High Frequency Stimuli		Low Frequency Stimuli	
Word	Frequency	Word	Frequency
FIERY	7	RAISIN	1
RECIPE	8	INDICT	2
GADGET	11	ERRATIC	3
RHYTHM	35	ADJOURN	4
BANQUET	9	PLUMBER	4
PAGEANT	12	BROCCOLI	1
DILEMMA	27	JEOPARDY	4
ENDEAVOR	5	NINETIETH	1
OCCASION	80	ACQUITTED	2
GRIEVANCE	6	AFFIDAVIT	2
RESERVOIR	13	INOCULATE	3
CONSCIOUS	46	PNEUMONIA	3
COMMITTEE	188	IRIDESCENT	0
DESCENDANT	7	OBSEQUIOUS	2
PICNICKING	16	ACRIMONIOUS	0
ASSESSMENT	30	COUNTERFEIT	1
OCCURRENCE	40	CONVALESCENT	1
RESTAURANT	53	CALISTHENICS	4
UNNECESSARY	16	PARAPHERNALIA	1
SPONTANEOUS	17	INFINITESIMAL	3
Mean	31.3	Mean	2.2

Table 3:

Percent Correct Spelling per Participant for Young, Older, and Oldest adults as a Function of Word Frequency, with SD in Parentheses.

Age Group	High Frequency Words	Low Frequency Words	Overall Percent Correct
Young Adults	72.1	54.2	63.3
	(15.9)	(15.7)	(14.4)
Older Adults	66.0	56.3	61.2
	(26.7)	(21.5)	(23.5)
Oldest Adults	56.0	47.3	51.6
	(23.4)	(21.2)	(21.8)

Table 4: Mean number of Same-pronunciation, Different-pronunciation and Overall Errors per Participant as a Function of Word Frequency, with SD in Parentheses.

	Mean Frequency of Errors per Participant				
	High Frequency Words		Low Frequency Words		Overall
Age Group	Same-Pronunciation Errors	Different-Pronunciation Errors	Same-Pronunciation Errors	Different-Pronunciation Errors	Errors
Young Adults	4.40	1.03	6.89	1.63	13.94
	(2.21)	(1.18)	(2.39)	(1.70)	(5.57)
Older Adults	4.80	1.48	5.92	2.20	14.40
	(3.55)	(1.85)	(2.93)	(2.50)	(8.49)
Oldest Adults	5.92	1.92	6.12	2.88	16.84
	(3.11)	(1.71)	(2.24)	(2.42)	(7.05)

Table 5: Mean Proportion (panel A) and Adjusted Mean Proportion (with Nelson Denny scores as covariate: panel B) of Same- and Different-pronunciation Errors per Participant as a Function of Word Frequency, with SD in Parentheses

A. Mean Proportion of Errors per Participant

	High Frequency Words		Low Frequency Words	
Age Group	Same-Pronuncia-tion Errors	Different-Pronuncia-tion Errors	Same-Pronuncia-tion Errors	Different-Pronuncia-tion Errors
Young Adults	.854 (.140)	.146 (.140)	.827 (.144)	.173 (.144)
Older Adults	.783 (.156)	.217 (.156)	.744 (.211)	.256 (.211)
Oldest Adults	.775 (.172)	.225 (.172)	.712 (.203)	.288 (.203)

B. Adjusted Mean Proportion of Errors per Participant

	High Frequency Words		Low Frequency Words	
Age Group	Same-Pronuncia-ton Errors	Different-Pronuncia-tion Errors	Same-Pronuncia-tion Errors	Different-Pronuncia-Tion Errors
Young Adults	.877 (.141)	.123 (.141)	.890 (.146)	.110 (.146)
Older Adults	.767 (.156)	.233 (.156)	.698 (.211)	.302 (.211)
Oldest Adults	.787 (.164)	.213 (.164)	.714 (.201)	.286 (.201)

Table 6: Mean Proportion of Same- and Different-Pronunciation Errors per Participant for Regularly- and Irregularly-Spelled Letters in High-Frequency Words, with SD in parentheses

	Mean Proportion of Errors per Participant			
	Regularly-Spelled Letters		Irregularly-Spelled Letters	
Age Group	Same-Pronunciation Errors	Different-Pronunciation Errors	Same-Pronunciation Errors	Different-Pronunciation Errors
Young Adults	.997	.003	.981	.019
	(.006)	(.006)	(.026)	(.026)
Older Adults	.994	.006	.973	.027
	(.011)	(.011)	(.039)	(.039)
Oldest Adults	.986	.014	.979	.021
	(.016)	(.016)	(.027)	(.027)

Table 7:

Percent Correct Spelling per Participant as a Function of Age for Words Containing versus Not Containing a Crossout, together with Overall (frequency-weighted) Percent Correct and SD in Parentheses.

Age Group	Words Containing a Crossout	Words Not Containing a Crossout	Overall Percent Correct
Young Adults	44.7 (26.2)	66.7 (15.3)	63.3 (14.4)
Older Adults	44.5 (33.9)	63.0 (23.0)	61.2 (23.5)
Oldest Adults	34.8 (32.7)	54.1 (21.9)	51.6 (21.8)

Table 8:

Percent Crossouts per Participant for Misheard versus Correctly-heard Stimuli as a Function of Age Group, with SD in Parentheses.

Age Group	Misheard Stimuli	Correctly-Heard Stimuli
Young Adults	7.1	15.0
	(23.9)	(6.1)
Older Adults	9.7	17.3
	(18.1)	(11.0)
Oldest Adults	22.6	13.4
	(39.4)	(10.1)

Figure Captions

Figure 1: A sample of top-down and lateral connections in NST for producing the word calendar at semantic, phonological, and orthographic levels. The broken top-down link indicates an inhibitory connection, and solid top-down links indicate excitatory connections. Nodes within the muscle movement systems for spoken speech, handwritten spelling and typed spelling have been omitted.

Figure 2: The adjusted mean percent correct spelling per participant using Nelson-Denny scores as covariate (left ordinate), and adjusted mean number of same-pronunciation and different-pronunciation errors per participant using Nelson-Denny scores as a covariate (right ordinate) for young, older, and oldest adults spelling high and low frequency words. The error bars indicate one standard error above the mean.

Figure 3: The probability per letter of same-pronunciation and different-pronunciation misspellings for the young, older, and oldest adults on regularly-spelled (left ordinate) versus irregularly-spelled letters (right ordinate: Note expanded scale) in high frequency words (see text for explanation). The error bars indicate one standard error above the mean.