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Aging on the Input versus Output Side: Theoretical Implications of Age-linked Asymmetries between
Detecting versus Retrieving Orthographic Information

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Abstract

This experiment tests for age-linked asymmetries predicted under Node Structure theory (NST; MacKay & Burke, 1990) between detecting versus retrieving orthographic information. Older adults detected that briefly presented words were correctly-spelled, e.g., endeavor, or misspelled, e.g., endeavuor, as readily as young adults. However, they were less able than young adults to retrieve the correctly- and incorrectly-spelled words that they had seen. These age-linked asymmetries were not due to educational factors, stimulus characteristics, sensory-level factors, task complexity, floor or ceiling effects, general slowing, or cohort-related activities, but comported with NST predictions and with similar asymmetries in a wide range of other studies. By contrast, repetition deficits in detecting and retrieving repeated- versus unrepeated-letter misspellings e.g., elderdly versus elderkly, were symmetric or equivalent in magnitude for young and older adults. Implications of these findings for a wide range of theories of cognitive aging and of repetition deficits are discussed.

Aging on the Input versus Output Side: Theoretical Implications of Age-linked Asymmetries between Detecting versus Retrieving Orthographic Information

This study reports the first systematic comparison of aging effects on the input versus output side of language processing. The input side of language involves perception of the letters and speech sounds that make up words, and comprehension of the meaning of words and sentences. The output side of language involves retrieval of words and speech sounds during speech production, and retrieval of letters in words during writing and typing. We first review the many studies that have examined effects of aging separately on either the input or output side of language, and argue that age effects in these studies are asymmetric: When age-linked deficits in sensory processing and in the ability to encode new information are controlled or factored out, input-side processes remain remarkably stable in old age, whereas output-side processes exhibit major declines. We then argue that this asymmetric pattern, if not due to experimental artifact, presents a fundamental challenge for theories of cognitive aging, which must explain why some aspects of information processing are so much more vulnerable to effects of aging than others: Theories that predict either sparing or impairment of verbal abilities across the board in old age do not fit this asymmetric pattern. Finally, we describe a theory that predicts two specific types of input-output asymmetry, and outline the present experiment, which tests these predictions and controls for possible artifacts in previous studies.

Language and Aging on the Input Side

The semantic priming paradigm has provided many dramatic demonstrations of age constancy on the input side: Laver & Burke (1993) reviewed results of 15 semantic priming studies indicating that presenting a word, e.g., doctor, causes automatic spread of activation to related words, e.g., nurse, without deficit in old age (see Burke & MacKay, 1997; and MacKay & Abrams, 1996, for more

recent reviews). Studies of word comprehension in sentences have demonstrated similar age constancy using off-line measures (for a recent review, see Burke & MacKay, 1997) and on-line measures of semantic processes as they occur during sentence comprehension (see e.g., Burke & Yee, 1984; Cohen & Faulkner, 1983; Light, Valencia-Laver, & Zavis, 1991; Madden, 1988; Stine & Wingfield, 1994; Wingfield, Alexander, & Cavigelli, 1994). These “on-line” data ruled out a major confound inherent in “off-line” or recall-based measures of comprehension, where age differences may reflect not word comprehension per se, but the process of forming new connections for linking comprehended words to their temporal and spatial context or source (for a review, see e.g., Burke & MacKay, 1997).

Language and Aging on the Output Side

Unlike language comprehension, language production is not immune to effects of aging: Spoken and written language production exhibit large age-related declines that are independent of the ability to encode new information (see Burke & MacKay, 1997, and MacKay & Abrams, 1998, for recent reviews). Older adults often complain of increased difficulty in retrieving words that they know they know (see e.g., Burke, MacKay, Worthley, & Wade, 1991), and their performance on a range of tasks is consistent with these complaints. For example, older adults in the tip-of-the-tongue (TOT) state can report fewer phonological features of a target word, such as its stress pattern and initial letter, and have fewer phonologically similar words come spontaneously to mind than do young adults (see e.g., Rastle & Burke, 1996). These and other age-linked problems in spoken word retrieval (see e.g., Au, Joung, Nicholas, Obler, Kass & Albert, 1995) have a close link to the access of phonological information because providing phonological cues to a target word reduces the age deficits (see e.g., Mitchell, 1989), but providing additional semantic information does not (Bowles & Poon, 1985).

Retrieval of orthographic information also exhibits age-linked declines. Young (age 17-23 years), older (age 60-71 years), and very old adults (age 73-88 years) in MacKay and Abrams (1998) heard irregularly spelled English words spoken slowly, clearly and repeatedly, and wrote the words down at their own pace on a sheet of paper. Despite having more education and higher vocabulary scores, the oldest adults correctly spelled high frequency words less often than the young adults, an age-linked decline that was unrelated to rated quality of prior training on spelling skills, to hours per week spent reading, writing, or solving crossword puzzles, and to age-linked declines in the ability to detect and correct errors in their written output. In addition, responses to a metamemory questionnaire indicated that the oldest but not the older adults were aware of their declining ability to spell.

Theories of Aging on the Input versus Output Side

What explains the asymmetric effects of aging in these separate studies of perception and of production? One possibility is experimental artifact: Participants and stimuli differed in the studies on perception versus production, and the perception tasks may have been “easier” than the production tasks. Such “artifact accounts” are consistent with the hypothesis that effects of aging on perception and production are symmetric or equivalent in magnitude. This “Symmetry hypothesis” derives from theories that postulate mirror image perception and production processes, and attribute cognitive aging to a single factor such as general slowing.

The Asymmetry hypothesis, that aging has disproportionately greater effects on production than perception, derives from theories where production processes are not the mirror image of perception processes, and where cognitive aging impairs production relatively more than perception. An example is the Transmission Deficit hypothesis, as embedded within the Node Structure theory (NST) of MacKay (1987). Because the present experiment tested several age-linked asymmetries

between detecting versus retrieving orthographic information predicted by this theory, we examine its mechanisms in detail.

Because MacKay & Abrams (1998) describe the top-down processes underlying orthographic retrieval in NST, these will not be reiterated here. Instead we elaborate on the bottom-up processes for orthographic detection and how these bottom-up processes differ from the top-down processes for retrieval. By way of illustration, consider the letter nodes in Figure 1 that represent the orthographic string aging¹ during both detection and retrieval in NST. For detection, these letter nodes are connected bottom-up to a single lexical node that represents the concept ‘aging’ (see Figure 1), and for retrieval, the lexical concept node for aging is connected top-down to these same letter nodes and to the systems of muscle movement nodes for writing and typing the word aging (not shown in Figure 1). What is important to note in Figure 1 is that top-down and bottom-up connections are asymmetric: the bottom-up links for perceiving the word aging converge many-to-one onto the lexical node for aging, whereas the top-down links for producing the word aging are one-to-one, i.e., only one node primes each letter node.

Under the Transmission Deficit hypothesis (MacKay & Burke, 1990), aging causes a statistical decrease in transmission of priming across connections between millions of nodes throughout the entire network. This means that age effects will be greatest when a node critical to a task receives priming from only a single source or connection within the network: If that one connection is defective, the critical node will be difficult to activate because no other sources of priming can offset the reduced priming across that connection. For example, a transmission deficit across the top-down link between the lexical concept and the letter node for [I] in Figure 1 would make [I] difficult to retrieve when writing or typing the word aging because no other source of priming could offset the transmission deficit. However, when perceiving the visual word aging, all

five bottom-up connections from its letter nodes simultaneously deliver priming to the lexical node for aging. Because the resulting summation of priming across these connections will tend to offset an age-linked transmission deficit across any one link, the word aging will be accurately perceived despite such a transmission deficit. The Transmission Deficit hypothesis therefore predicts small or nonexistent age deficits in perceiving orthography, despite large age deficits in producing or retrieving orthography.

The Transmission Deficit hypothesis also explains the phenomenon of age-constancy in semantic priming studies. The semantic system consists of a vast number of lexical nodes and propositions that are either directly or indirectly interconnected with one another. Figure 1 illustrates a simplified semantic memory consisting of three propositions, namely aging causes frailty, aging causes cataracts, and aging is not for the timid. These three propositions are interconnected via their common links to the lexical node for aging, which will also have indirect links to numerous other concepts via the many other propositions stored in semantic memory. For example, if the semantic memory in Figure 1 also contains the proposition cataracts cause blindness, then the concepts aging and blindness will have an indirect link via the propositions aging causes cataracts and cataracts cause blindness. Because of these indirect links between aging and blindness, activating the concept aging in the semantic priming paradigm will prime the concept blindness, enabling faster responses to this semantically related word.

Consider now the phenomenon of age-constancy in semantic priming tasks. Semantically related concepts such as aging and blindness are more likely to have indirect links for older than young adults because over the course of their (longer) lifetimes, older adults have acquired more general knowledge in the form of propositions such as aging can cause glaucoma, and glaucoma can cause blindness. As a result of this enriched semantic network, more “parallel” connections will link

semantically related concepts in the memory systems of older than young adults. Priming will therefore converge across these additional, parallel connections and summate to a greater extent for older adults, thereby offsetting transmission deficits across any one connection. As a result, semantic priming effects will be as large or larger for older adults relative to young adults, as Laver & Burke (1993) observed.

The Present Paradigm: Detection versus Retrieval of Orthographic Information

To address the issue of artifacts in previous studies of perception versus production, the present study used exactly the same participants and stimuli in perception and production tasks that were comparable in difficulty, as measured post hoc. Participants saw briefly presented words that were either correctly-spelled or deliberately misspelled, sometimes by adding a single “target” letter. For example, [U] is the target letter added to endeavor in the misspelling endeavuor (target letter underlined), and these target letters were the focus of many of our analyses. Participants were instructed that the words they would see were either correctly-spelled or misspelled (in unspecified ways), and that they had two tasks. The first was a perception task: to respond “right” to indicate correct spelling or “wrong” to indicate error detection. The second, production/retrieval task was to write out the spelling of the word, exactly as presented.

The Symmetry hypothesis predicted no age-linked asymmetries between the detection versus retrieval tasks, i.e., no difference in effects of aging on detecting versus retrieving misspelled and correctly-spelled words. However, the Asymmetry hypothesis predicted two age-linked asymmetries for the detection versus retrieval tasks: a “Correct Spelling Asymmetry”, i.e., a smaller age-linked deficit in detecting than in retrieving the correct spelling of words that were recognized as correctly-spelled; and a Misspelling Asymmetry, i.e., a smaller age-linked deficit in detecting misspelled stimuli than in retrieving misspelled stimuli, given error detection.

We also adopted the logic of “double dissociation” procedures in neuropsychology (see Parkin, 1996, pp. 9-11) to test whether the Misspelling Asymmetry is specific to aging or is more general in nature, such that any factor that influences the retrieval of misspellings exhibits the same interaction with aging or with task as predicted for the Misspelling Asymmetry. As the first step in this double dissociation logic, we introduced into a subset of our materials a variable with known effects on the retrieval of misspellings, namely repetition. That is, the added letter created either a repeated- or unrepeated-letter misspelling of these words. In repeated-letter misspellings, the added or “target” letter repeated a “pretarget” letter earlier in the word, e.g., *elderdly* (target letter underlined, pretarget in italics), whereas in unrepeated-letter misspellings, the target letter differed from all other letters in the word, e.g., *elderkly*. Based on previous results for young adults in a related paradigm (MacKay, 1969), we predicted a repetition deficit (RD) in perception and retrieval, i.e., better detection and retrieval of unrepeated- than repeated-letter misspellings. This being the case, the double dissociation logic proceeds as follows: If RD is greater in retrieval than in perception, and especially for older adults, this would indicate that the Misspelling Asymmetry is general in nature and does not require an explanation within theories of cognitive aging. On the other hand, if RD is equivalent in retrieval and perception for both young and older adults, this would indicate that the Misspelling Asymmetry is specific to aging, and requires an explanation within theories of cognitive aging.

Effects of aging on RD were also of interest for subsidiary reasons: MacKay, Miller, & Schuster (1994) and MacKay & Miller (1996) demonstrated that interactions between aging and word-level repetition can directly test four general hypotheses as to the causal basis of RD in the standard RD paradigm (see e.g., Kanwisher & Potter, 1990; and MacKay & Miller, 1994), where words are presented one on top of the other using the rapid serial visual presentation (RSVP)

technique. The Appendix outlines the pros and cons of the present paradigm versus the standard paradigm for testing these four general RD hypotheses, and describes age effects predicted under these hypotheses for the present paradigm, and how these predictions relate to present results and to familiar age-linked effects such as binding deficits (see, e.g., Burke & MacKay, 1997, for a review) and inhibition deficits (see, e.g., McDowd, Oseas-Kreger, & Filion, 1995). Table 2 summarizes our full set of hypotheses and predictions.

Method

Participants

The 72 participants fell into young and older groups with means and standard deviations (SD) for standard background characteristics shown in Table 1. All were native English speakers who reported no neurologic problems, no serious medical problems, and normal or corrected-to-normal vision. The 36 young adults (14 males, 22 females) were 17-23 years old and participated in return for course credit from introductory psychology classes at UCLA. The 36 older adults (17 males, 19 females) were 62-85 year old members of the UCLA Cognition and Aging Lab pool (current N=198) who received \$10 plus travel expenses from their homes in the greater Los Angeles area. Most were recruited from the UCLA Alumni Association, local churches, and senior citizen centers. The age groups differed at $p < .05$ on only two background characteristics: Older adults had more years of education than young adults, $t(68)=6.14$, $p < .001$, and higher Nelson-Denny vocabulary scores than young adults, $t(68)=5.88$, $p < .001$.²

Materials

The materials consisted of 100 words that fell into two categories: Type I words (N=45) and Type II words (N=55). Type I words were selected from Faucett & Maki (1932), had relatively high frequency of occurrence (mean 80.4 per million; Francis & Kucera, 1982), and were 8.3 letters long

on average (range 7-10 letters). Besides testing for asymmetries, Type I words were designed to assess effects of repetition on detection and retrieval of misspellings: Each Type I word appeared in three different spelling conditions, counterbalanced across participants: correct spelling (e.g., elderly), unrepeated-letter misspelling (e.g., elderkly), and repeated-letter misspelling (e.g., elderdly). As in these examples, Type I words were misspelled by adding a single target letter to the original word, and always differed in pronunciation from the original word. In unrepeated-letter misspellings, e.g., elderkly, the added target letter differed from all other letters in the original word, whereas in repeated-letter misspellings, the target letter repeated a letter earlier in the original word, e.g., elderdly. Target letters always had identical height characteristics in repeated- and unrepeated-letter misspellings and always occupied the same position within the original word, as in elderkly and elderdly, and always resulted in misspellings that were phonologically and orthographically acceptable in English. Pretarget letters were the identical letter that preceded the added letter in repeated-letter misspellings, e.g., the initial d in elderdly, and the corresponding letter in unrepeated-letter misspellings, e.g., the d in elderkly. Pretarget letters never began a misspelled word, and preceded target letters by one intervening letter (e.g., faculty misspelled as facultly), two intervening letters (e.g., reverence misspelled as revervence), or three intervening letters (e.g., bachelor misspelled as bachealor).

Type II words were similar to Type I words except that they came from Norback (1974), were “difficult-to-spell,” never involved the letter repetition factor, and only appeared in one correctly- or incorrectly-spelled version ranging in length from 5-12 letters. The 20 Type II misspellings, e.g., quadrant misspelled as quadrent, were formed by either replacing or omitting a single letter in the original word, e.g., handkerchief misspelled as hankerchief. Type II words were designed to prevent

participants from developing strategies attuned to the repetition factor, and to test for age-linked asymmetries independently of the repetition factor.

Choice of Presentation Times

We chose three overlapping presentation times for young and older adults based on two sets of criteria. One set was designed to equate the relative difficulty of the perception and production tasks: We adjusted presentation rates until performance of young pilot participants was about equal in the two tasks for both correctly and incorrectly-spelled stimuli. The second set of criteria involved procedures developed in MacKay et al. (1994) to avoid ceiling and floor effects, and possible confounds between RD, aging, and performance levels for unrepeated- minus repeated-letter targets. Using these criteria, 290ms/word was used for both groups, enabling standardized between-group comparisons, and the remaining rates were 230- and 260ms/word for young adults and 340- and 390ms/word for older adults. These rates could be considered fast, medium, and slow for young and older adults, with performance that was above a predetermined floor (30%) and below a predetermined ceiling (90%) for both groups.

Procedure

Participants first provided background information, and then completed a questionnaire concerning activities with possible relations to spelling ability: hours/week spent reading, writing, solving crossword puzzles. Participants also used five-point scales to evaluate their current spelling ability and to rate how rigorously their grade school taught spelling skills ("5" for "rigorous" training, and "1" for "lax" training). Questionnaires for the older adults also contained an identical five point scale for rating their remembered spelling ability at age 20. Participants then saw six practice stimuli, two at each rate, with one word spelled correctly, and five misspelled by repeating, adding, omitting, and replacing a letter. Written instructions informed participants that words would appear briefly for

varying durations, centered on the screen before them, with some words spelled correctly and others incorrectly.

In the experiment proper, participants saw the 45 Type I words interspersed among the 55 Type II words, which occurred in three differing random orders across participants. Type I words appeared equally often in the three spelling and rate conditions, crossed over nine different random orders that were assigned to participants in each group by order of arrival. Type II words also appeared equally often in the rate conditions across the nine versions of the sentence. However, in order to maintain a high level of attention and performance over the experiment, the experimenter verbally informed participants as to the upcoming word for a small subset of Type II words that was counterbalanced across participants, e.g., “The next correctly or incorrectly-spelled word is quadrant” for the misspelled stimulus quadrent. These “primed” words received no further analysis.

Materials were presented via Mac IICI computer using PsyScope software (Cohen, MacWhinney, Flatt, & Provost, 1993), beginning with a 2000ms warning (“Get ready for the next word”), followed by a 1200ms fixation point prior to word presentation. Next came a string of 14 question marks (????????????), signaling participants to say “right” (indicating that the word was correctly-spelled) or “wrong” (otherwise). Participants next printed exactly what they had seen on a numbered sheet, (mis)spelling the word as they had seen it (mis)spelled, guessing at the spelling if necessary. The experimenter pressed any key to initiate the next trial.

Results

Table 2 summarizes our primary and secondary hypotheses and how they relate to our results, which we report under the headings Main, Subsidiary, and Appendix. Main Results include analyses relevant to the Correct Spelling and Misspelling Asymmetries discussed in the introduction. Subsidiary Results include analyses of repetition and rate related to age-linked asymmetries. The

Appendix includes results related to our secondary hypotheses concerning age-linked effects of repetition and the causal basis of RD. Unless indicated otherwise, all analyses and figures involved Type I stimuli, while data for Type II stimuli are presented in tables.

Main Results

Our simplest dependent measures were detection probability (the probability of correctly responding “right” or “wrong” in the detection task), and retrieval probability (the probability of correctly reproducing the stimuli exactly as presented, with each stimulus letter in corresponding order in the written record). Table 3 shows mean detection probabilities per participant as a function of age, rate, and spelling condition (correctly-spelled, repeated-, and unrepeated-letter misspellings). Table 4 shows mean retrieval probabilities as a function of age, rate, and spelling condition.

The more complex, conditional measures described next were necessary to conclusively establish age-linked asymmetries in our retrieval data. The conditional measures in Figure 2 collapsed across rate and excluded retrieval trials where participants failed to correctly perceive the stimuli in the detection task, thereby ensuring that detection effects did not contaminate subsequent retrieval effects, an essential precaution for establishing asymmetries between detection and retrieval. Conditional retrieval probability for correctly-spelled stimuli is the probability of correct retrieval given correct perception that the stimulus was correctly-spelled in the detection task, and is shown as a function of age group in Figure 2 (right panel). Conditional retrieval probability for misspelled stimuli is the probability of correct retrieval given correct detection that the stimulus was misspelled in the detection task, and is shown as a function of age group in Figure 2 (right panel). To simplify exposition, our results only include statistical analyses for these conditional retrieval measures, which were more appropriate and in any case led to the same basic conclusions as analyses of the unconditional data in Tables 3 and 4.

The Asymmetry for Correctly Spelled Stimuli

For correctly-spelled Type I stimuli, a 2 (age) x 2 (detection vs. retrieval task) multivariate analyses of variance (MANOVA) on detection probabilities and conditional retrieval probabilities in Figure 2 indicated no main effect of age, $F < 1$, or of task, $F(1,70)=2.70$, $MSe=.01$, $p > .104$. However, the age x task interaction was significant, $F(1,70)=5.73$, $MSe=.01$, $p < .019$, and further analyses indicated that detection probabilities did not differ for young versus older adults, $F < 1$, but conditional retrieval probabilities were greater for young than older adults, $F(1,70)=5.30$, $MSe=.01$, $p < .024$. This Correct Spelling Asymmetry was not due to ceiling effects because performance was closer to ceiling for older adults in the detection task, but closer to ceiling for young adults in the retrieval task (see Figure 2), so that ceiling effects would have worked against this asymmetry.

Correctly-spelled Type II Stimuli: A Replication. An analysis of correctly-spelled Type II words ($N=35$) replicated the Correct Spelling Asymmetry for a different set of stimuli. Table 5 shows the mean detection probabilities for correctly-spelled Type II words as a function of age group, together with conditional retrieval probabilities given correct detection. A 2(age) x 2(task: detection vs. conditional retrieval) MANOVA on these data indicated no main effect of age, $F(1,70)=1.42$, $MSe=.01$, $p > .236$, or task, $F(1,70)=2.81$, $MSe=.01$, $p > .097$, but a significant age x task interaction, $F(1,70)=6.11$, $MSe=.01$, $p < .016$. Further analyses indicated no age difference in detection, but a large age difference favoring the young in retrieval when correctly-spelled Type II words were recognized as correctly-spelled, $F(1,70)=4.44$, $MSe=.01$, $p < .039$. This Correct Spelling Asymmetry for Type II words was not due to ceiling effects because older adults were closer to ceiling than young adults in the detection task, but further from ceiling in the retrieval task (see Table 5).

Correlations with Activities and Background Characteristics. Young and older adults differed at $p < .05$ on only one reported activity: Older adults reported spending significantly more hours per week

doing crossword puzzles than young adults, $t(64)=2.31$, $p<.024$. However, our main dependent measures (e.g., correct detection and written spelling retrieval for correctly-spelled words) did not correlate reliably with time spent doing crossword puzzles at $p<.05$ for either young or older adults.

Multivariate analyses of covariance with education level and Nelson-Denny scores as covariates yielded only one reliable regression with our main dependent measures: Education correlated negatively with correct detection probability for older adults, $r(36)= -0.385$, $p<.02$, an outcome that could only have worked against the Correct Spelling Asymmetry because older adults had more education than young adults. This same correlation for young adults was positive, $r(36)= 0.312$, and unreliable at $p<.05$.

The Asymmetry for Misspelled Stimuli

For misspelled Type I stimuli, Figure 2 (left panel) shows mean detection probabilities as a function of age, and Figure 2 (right panel) shows mean retrieval probabilities conditional on correct detection. A 2 (age) x 2 (detection vs. retrieval task) MANOVA on these data yielded no main effect of age, $F(1,70) = 1.98$, $MSe=.05$, $p>.164$, but a main effect of task, $F(1,70)=382.05$, $MSe=.01$, $p < .001$, with higher detection probabilities than retrieval probabilities. Consistent with a Misspelling Asymmetry, the age x task interaction was also significant, $F(1,70)=6.09$, $MSe=.01$, $p < .016$, with no age difference for detection of misspellings, $F < 1$, but a large age difference favoring young adults for retrieval of misspellings that were detected as misspelled, $F(1,70)=5.53$, $MSe=.03$, $p < .021$.

Misspelled Type II Words: A Replication. Analyses of misspelled Type II words ($N=20$) replicated the Misspelling Asymmetry for a different set of misspellings. Table 5 shows the mean detection probabilities for Type II misspellings as a function of age group, together with conditional retrieval probabilities given correct detection. A 2(age) x 2(task: detection vs. conditional retrieval) MANOVA on these data indicated no main effect of age, $F(1,70)=2.83$, $MSe=.03$, $p > .096$, but a

main effect of task, $F(1,70)=29.28$, $MSe=.01$, $p < .001$, with better detection than retrieval. The age x task interaction was also significant, $F(1,70)=13.98$, $MSe=.01$, $p < .001$, due to a Misspelling Asymmetry: There was no age difference in detection, $F < 1$, but a large age difference favoring young adults in conditional retrieval, $F(1,70)=11.75$, $MSe=.02$, $p < .001$. This Misspelling Asymmetry for Type II words was not due to floor or ceiling effects because performance was closer to ceiling for older adults in the detection task but closer to ceiling for young adults in the retrieval task (see Table 5), indicating that ceiling effects would have worked against a Misspelling Asymmetry for Type II words. This replication indicates that the Misspelling Asymmetry cannot be attributed to factors specific to Type I misspellings.

Length-Detection Analyses. Type II replacement misspellings, e.g., quadrant misspelled as quadrent, exhibited the age x task (Misspelling Asymmetry) interaction at $p < .001$ (see Table 5), and were detected with higher probability than different-length (i.e., all other) misspellings, $p < .001$. These findings rule out an “expected length account” whereby detecting the unusual length of Type I misspellings provided the basis for the Misspelling Asymmetry. Although Type I stimuli always differed in length from the original or expected word, replacement misspellings were always the same length as the original word and could not have been detected on the basis of expected word length.

Subsidiary Results Involving Rate and Repetition

Detection and Retrieval Analyses as a Function of Rate

Rate had no effect on the probability of detecting either correctly- or incorrectly-spelled Type I stimuli. A 2 (age) x 2 (correct vs. incorrect spelling) x 3 (rate: fast, medium, and slow) MANOVA yielded a main effect of spelling condition, $F(1, 70)=*123.16$, $MSe=.05$, $p < .001$, with better detection of correct than incorrect spelling, and a main effect of rate, $F(2, 140)=3.15$, $MSe=.01$, $p < .046$, with better detection at the slowest rate. However, there was no main effect of age, and no reliable

interactions involving rate (largest $F=2.98$, smallest $p=.054$). Similar analyses for detecting correctly- and incorrectly-spelled Type II words likewise yielded no effects of age or rate, and no interactions involving rate. MANOVAs using only the data for the single rate shared by young and older adults (290 ms/word) likewise yielded no age effects or interactions involving age. Independent MANOVAs for retrieval of correctly- and incorrectly-spelled words that were detected as such also yielded no effects of rate, and no age x rate interactions for either Type I or Type II stimuli. These findings indicate that rate was not a factor on either the detection side or the production side of the Misspelling and Correct Spelling Asymmetries.

Symmetric Effects of Repetition for Task and Age: The Double Dissociation Data

To determine whether repetition exhibits the same interaction with aging or with task as the Misspelling Asymmetry, we conditionalized correct recall of repeated- and unrepeated-letter misspellings on correct detection as before, thereby ensuring that effects of repetition on perception did not influence or contaminate effects of repetition on retrieval.³ We also took two steps to ensure that effects of repetition on retrieval were independent of age-linked declines in the ability to spell (see Figure 2; also MacKay & Abrams, 1998). One was to define correct retrieval as correct inclusion of the added or target letter, i.e., correct spelling of the entire word was unnecessary. The other was to conditionalize correct target recall on inclusion of the pretarget letter: Responses containing missing pretargets, e.g., wilderness misproduced as weldness, and calendear misproduced as calander, were discarded for logical and theoretical reasons that have been noted in many recent studies of RD (see e.g., MacKay et al., 1994, MacKay, Abrams, Pedroza, & Miller, 1996): If a participant does not perceive the pretarget, a repeated-target trial is unrepeated from a psychological point of view, so that including these trials in the means would underestimate the true degree of retrieval RD. These “double conditional analyses” met the criterion of equivalent rates of data discard across groups (see

MacKay et al., 1994; MacKay & Miller, 1996): 31% for young adults and 27% for older adults, with only two participants lost due to empty cells in our main MANOVAs.

Figure 3 shows mean detection probabilities (left panel) and double conditional probabilities of correct retrieval (right panel) for repeated- and unrepeated-letter targets as a function of age group, collapsed across the three rates. A 2 (age) x 2 (repetition) x 2 (task: detection vs. retrieval) MANOVA on these data revealed a main effect of age, $F(1,68)=4.44$, $MSe=.07$, $p < .039$, with better performance for the young than older adults; a main effect of repetition, $F(1,68)=244.10$, $MSe=.04$, $p < .001$, with better performance for unrepeated- than repeated-letter targets; and a main effect of task, $F(1,68)=12.80$, $MSe=.05$, $p < .001$, with better performance in the detection task than in the retrieval task. The age x task interaction was also significant, $F(1,68)=9.98$, $MSe=.05$, $p < .002$, with no age difference in detection, $F < 1$, but a large age difference favoring the young in target recall, $F(1,68)=12.05$, $MSe=.07$, $p < .001$. No other interactions were significant, smallest $p > .154$. Similar analyses using only the single rate shared by young and older adults gave identical results. These results indicate that repetition has powerful effects that are symmetric with respect to task (effects of repetition were similar in detection and recall), and with respect to age (effects of repetition were similar for young and older adults).

Floor and Ceiling Effect Analyses. Because detection probabilities for repeated-letter misspellings approximated coin toss levels of accuracy (0.5) for both the young and older adults (see Figure 3, left panel), our participants may have been simply guessing in this condition, effectively introducing a 50% floor that might have eliminated a potential age x repetition interaction in the detection data. We therefore divided older participants into two groups with detection levels for repeated-target misspellings that were above versus below their group median, and did the same for young participants. Performance for both the young and older above-the-repeated-median groups was

well above the hypothesized 50% floor, but a comparison of these groups yielded no age effect $*(F < 1)$ - **the Dec 1997 paper had a main effect of age favoring old, $F(1,32)=5.01$, $MSe=.02$, $p < .032$; I'm assuming you mean there was no age x rep interaction, but it's not clear -**, ruling out this "guessing floor" account of the Misspelling Asymmetry. Three additional MANOVAs on data involving split groups ruled out other floor and ceiling accounts of the non-significant age x repetition interactions.

Discussion

Accounts of Asymmetries Involving Correctly Spelled Stimuli

What accounts for the Correct Spelling Asymmetry? Why was there a large age-linked deficit in retrieving the correct spelling of words that were recognized as correctly-spelled, but no age-linked deficit in detecting that the same words were correctly-spelled? The Correct Spelling Asymmetry is consistent with the Asymmetry hypothesis, that perception and production are not mirror image processes, and that aging has disproportionately greater effects on production than perception. One particular Asymmetry hypothesis, the Transmission Deficit hypothesis of MacKay and Burke (1990), explains the Correct Spelling Asymmetry and a wide range of other findings suggesting age-linked asymmetries between production and perception in terms of the differing structure of top-down versus bottom-up connections. Age effects are greatest under the Transmission Deficit hypothesis when a node critical to a task receives priming from only a single source or connection within the network, and this "single source condition" holds for the top-down connections for retrieving both phonology and orthography (see Figure 1). Age-linked deficits on the output side in the present study therefore comport with the Transmission Deficit hypothesis and with the many studies reviewed elsewhere (e.g., MacKay & Abrams, 1998) that demonstrate age-linked deficits in retrieving the phonology and orthography of familiar words.

Turning to the input side, age effects are small or non-existent under the Transmission Deficit hypothesis when a node critical to a task receives priming simultaneously from more than one source or connection within the network, and this “multiple source condition” holds for the bottom-up connections for perceiving familiar words within the phonological and orthographic system (see Figure 1). The age-constancy in perceiving correctly-spelled words as correctly spelled in the present experiment are therefore consistent with the Transmission Deficit hypothesis and with the many studies noted in the introduction that demonstrate small or nonexistent age effects on the input side.

We turn now to some unlikely accounts of the Correct Spelling Asymmetry. One is the hypothesis that cohort-related educational deficiencies affected the ability of older adults to retrieve the spelling of high frequency words in the present study: Contrary to this hypothesis, the older adults were more educated than the young adults, and they rated the rigor with which their grade schools taught spelling skills no less highly than young adults. Moreover, education level of older adults correlated negatively with the ability to detect whether words were correctly- or incorrectly-spelled, an outcome that could only have worked against the Correct Spelling Asymmetry. Present results also rule out other possible cohort effects related to how many hours/week participants spent reading, writing, and solving crossword puzzles: Only one of these factors correlated reliably with cohort, and it was unrelated to the probability of detecting and retrieving correct spelling.

The form of the Correct Spelling Asymmetry also rules out sensory- or receptor-level artifacts in the asymmetric effects of aging on the input versus output side: Age-linked sensory deficits could only cause increased perceptual errors for older relative to young adults for misspelled and correctly-spelled words, contrary to present results. Nor can the Correct Spelling Asymmetry be explained in terms of task difficulty such that older adults perceived correctly-spelled words as correctly spelled in the perception task, but recalled these words as misspelled in the production task because the

perception task was easier or “less complex” than the production task, and therefore less susceptible to age-linked declines in performance. Contrary to this hypothesis, performance level of young adults was numerically higher for the production task than for the perception task (see Figure 2), which suggests that, independent of the age factor, the perception task was at least as difficult as the production task in the case of correctly-spelled stimuli. Performance for correctly spelled words was also numerically higher for older adults in the production task than for young adults in the perception task (see Figure 2), suggesting that the production task per se was not difficult for the older adults. The similar pattern of results for Type II words (see Table 5) also argues against a task difficulty hypothesis.

Another unlikely account of the Correct Spelling Asymmetry points to the fact that participants always executed the perception task before the production task. Consequently, older adults may have forgotten perceived details of the stimuli at the time of recall, and therefore tended to misrecall correctly-spelled words as misspelled more often than young adults. Contrary to this hypothesis, however, performing the YES-NO response in the detection task took on the order of a second, and young and older adults usually do not differ in memory tasks with delays of that magnitude (see Craik, 1977, for a review). Nor is there any reason to believe that when recalling a correctly-spelled word that they perceive to be correctly spelled, older adults cannot remember a single item of information (“correct”) for a second or two. In addition, if forgetting was the basis for the Correct Spelling Asymmetry, then contrary to present data, age differences should have been smaller in retrieving frequently encountered, correctly-spelled words, than in retrieving misspelled forms which they had encountered only once. Moreover, having the perception task precede the production task provides the strongest possible case for a Correct Spelling Asymmetry. If the production task had preceded the perception task, errors on the perception task could be attributed

both to forgetting and to attempts to maintain consistency with the prior written response, which would more likely be in error for older than young adults (see MacKay & Abrams, 1998). Or given a recall task with no prior perception task, it could be argued that older adults more often misperceived the stimulus or forgot whether it was correctly- or incorrectly-spelled while writing down their response. As it was, we observed an age-linked increase in errors on the production task even when participants just saw the correctly-spelled word, and even though they probably tried to maintain consistency with their (correct) response in the detection task. Further, this age-linked increase in retrieval errors occurred even though the older adults could see what they had written, and determine whether, when read back, it matched what they meant to write.

Another unlikely account of the Correct Spelling Asymmetry is that our observed age-linked declines in spelling retrieval reflect transient or readily correctable errors. MacKay and Abrams (1998) ruled out this hypothesis by using procedures that de-emphasized response speed and minimized the likelihood of transient errors (e.g., self-paced trials, and slowly presented stimuli). Consistency of present results with those of MacKay and Abrams therefore suggests that misspellings of correctly-spelled words by older adults in the present study were not transient errors in spelling retrieval.⁴ MacKay and Abrams also ruled out other factors that might seem relevant to the present age-linked deficits in retrieving correct spelling: a variety of potential cohort effects, general slowing in older adults, and declines in the ability of older adults to monitor or detect errors in their written responses. At the same time, however, present results go beyond the MacKay and Abrams (1998) findings by indicating that older adults will often misspell a word despite having just seen the word spelled correctly and despite having just responded that the word was spelled correctly.

Another unlikely account of the Correct Spelling Asymmetry is the hypothesis that perception of familiar, correctly-spelled words involves wholistic or Gestalt-like processes that are rapid,

automatic, and parallel in nature (see Barron, 1980), and therefore immune from effects of aging, whereas retrieval of correct spellings is slow, deliberate, and sequential in nature, and therefore susceptible to age-linked decline. This hypothesis fails to explain the parallel nature of the Correct Spelling and Misspelling Asymmetries in our data, and predicts that replacement misspellings, e.g., quadrant misspelled as quadrent (which resembled the original, correctly-spelled word in overall shape or wholistic Gestalt more so than misspellings formed by adding a letter, e.g., endeavor misspelled as endeavuor, or by omitting a letter, e.g., handkerchief misspelled as hankerchief) should not exhibit a Misspelling Asymmetry, and should give rise to more misperceptions than addition or omission misspellings, contrary to present results.

Another unlikely account of the Correct Spelling Asymmetry is the Symmetry hypothesis outlined in the introduction: Theories that attribute cognitive aging to a single factor such as general slowing, and view perception and production as mirror image processes do not predict the Correct Spelling Asymmetry, and can only explain it as an artifact. However, use of exactly the same participants and stimuli in the present perception and production tasks rules out two possible artifacts in the many studies that have examined effects of aging separately on perception versus production. Results discussed earlier also rule out artifacts related to cohort, age-linked sensory deficits, ceiling and floor effects, task difficulty effects, task order effects, insensitivity of our perceptual measure due to chance level responding, and insufficient power in our design (see Appendix).

Accounts of Asymmetries Involving Misspelled Stimuli

We observed no age-linked deficits in detecting that a word was misspelled, but large age-linked deficits in retrieving the spelling of a word that participants recognized as misspelled. This Misspelling Asymmetry is consistent with predictions of the Asymmetry hypothesis discussed earlier

and is embodied in theories such as NST, where perception and production are not mirror image processes, and where cognitive aging impairs production more so than perception.

Results for misspelled words did not support the Symmetry hypothesis embodied in theories that attribute cognitive aging to a single factor such as general slowing, and view perception and production as mirror image processes. Under the Symmetry hypothesis, the Misspelling Asymmetry is an artifact, but present results did not support artifactual accounts of the Misspelling Asymmetry based on age-linked sensory deficits, ceiling and floor effects, task order effects, differing activities or background characteristics of our participants, differing stimuli in the perception versus production tasks, insensitivity of our perceptual measure due to chance level responding, and insufficient power in our design (see Appendix). The Misspelling Asymmetry was also not due to length detection processes involving Type I misspellings: Analyses of Type II replacement misspellings (which did not differ in length from the original word) ruled out this hypothesis. Nor was the Misspelling Asymmetry due to task difficulty because performance level of the young adults was greater for retrieving than for detecting Type II misspellings (see Table 5), suggesting that, independent of the age factor, the perception task was at least as difficult as the production task for misspelled words.

Also problematic for Symmetry theories, at least one factor that affects retrieval of misspellings does not exhibit the same interaction with either age or task as the Misspelling Asymmetry. Specifically, repetition had strong effects that were symmetric or equivalent in magnitude for both young and older adults and for both the detection and retrieval tasks. This double dissociation pattern suggests that the Misspelling Asymmetry is age-specific, and must be explained in theories of cognitive aging.

Subsidiary Issues

Aging and Error Detection

The ability to detect whether a correctly-spelled word is correctly spelled remained constant with age in the present data, and so did the ability to detect whether misspelled words are misspelled, consistent with the Asymmetry hypothesis, and with the results of Mahoney (1997), that young and older adults are equally able to detect self-produced phonological errors. Nonetheless, present results contrast with the report of Valencia-Laver (1992) that older adults correct (and presumably detect) self-produced lexical substitution errors, e.g., “Turn left, I mean, right”, reliably less often than young adults in a route-description task (see also MacKay, 1992). Perhaps age constancy in error detection only holds for some types of errors or some levels of language.

Present error detection results are also relevant to the processing resolution hypothesis of Allen, Madden & Slane (1995), Allen, Madden, Weber, & Groth (1993); and Stadtlander (1995), that perceiving letter level codes demands high processing resolution that is especially difficult for older adults because age-linked “internal noise randomly changes visual features” at a central perceptual level, i.e., independent of age-linked sensory deficits. However, if aging causes random changes in visual features during perception, the ability to detect correct spelling should decline with aging in the present paradigm because a correctly-spelled word with altered visual features should often be misperceived as misspelled. The fact that detecting correct spelling remained constant with aging in the present data therefore contradicts the processing resolution hypothesis. Similarly, older adults with deficits in processing resolution should be less able to detect added-letter misspellings than young adults, contrary to the present data indicating age-constancy. One possible resolution of these discrepant conclusions is that the Allen et al. task involved perception of words typed in novel formats (mixed upper and lower case, together with unusual patterns of letter spacing) that may have required new connection formation. The Allen et al. results may therefore reflect well-established age

deficits in new connection formation (see e.g., MacKay & Burke, 1990, for a review) rather than age-linked declines in processing resolution.

Our observed age-constancy in detecting misspellings also contradicts the hypothesis that due to sensory deficits, or due to greater experience with language, or both, older adults do not process each letter in familiar words, but tend to rely on “context”, in this case, the phonological and orthographic redundancy that exists within correctly-spelled words. Such “reliance on context” might enable older adults to detect that correctly-spelled words are correctly spelled without processing each letter, but should frequently cause older adults to misperceive misspelled words as correctly spelled. This is inconsistent with the present finding that detecting misspellings remained constant as a function of age.

Our observed age constancy in detecting repeated- and unrepeated-letter misspellings also contradicts another seemingly plausible hypothesis: that the ability to detect novelty is especially susceptible to effects of aging, and that novelty plays a role in detecting unrepeated-letter misspellings such as elderkly because the added letter is novel to the word, but plays no role in detecting repeated-letter misspellings such as elderdly because the added letter is a familiar component of the word. This novelty detection hypothesis predicts a much larger age-linked deficit in detecting unrepeated-letter misspellings than in detecting repeated-letter misspellings, contrary to present data.

Effects of Aging on RD

Effects of aging on RD in the present paradigm are relevant to the issue of whether there exists more than one type of RD. RD in the present paradigm was similar in magnitude for perception and retrieval, similar in magnitude across a wide range of presentation rates, and similar in magnitude for young and older adults. This pattern contrasts with results for standard-paradigm RD, where RD

has been shown to decrease as a linear function of presentation time, and where older adults exhibit more RD than young adults across a wide range of presentation rates (MacKay et al, 1994). Perhaps these contrasting empirical results reflect methodological differences between the standard RSVP paradigm versus the present paradigm (see the Appendix for detailed procedural comparisons).

Or perhaps the contrasting results have a parsimonious explanation in terms of some single, underlying cause. We do not currently understand how this “universal RD mechanism” might work. However, to stimulate research that may help understand it, we will tentatively postulate two theoretically distinct classes of RD: surface- versus deep-RD, analogous to the concepts of surface- versus deep-dyslexia and surface- versus deep-dysgraphia (see e.g., Parkin, 1996, pp. 167-180). Surface-RD occurs in both detection and retrieval, involves existing nodes representing highly practiced orthographic and phonological units in familiar words, and does not interact with aging (see Appendix). In contrast, deep-RD only occurs in sentence processing, it increases as a function of aging, and it is linked to the process of forming new connections between words and phrases in sentences (see MacKay et al., 1994; MacKay & Miller, 1996). Whether deep-RD occurs in both perception and retrieval has yet to be established for sentences in the standard RSVP paradigm. However, deep-RD is strongly influenced by syntactic/semantic factors, and underlies the semantic blindness phenomenon demonstrated by MacKay and Miller (1994). MacKay and Abrams (1994) also demonstrated a type of deep-RD in lists that increases in magnitude when repeated words occur in familiar phrases such as good night and night gown rather than in lists of unrelated words. Because phrases are fundamentally syntactic/semantic entities, this finding is consistent with the semantic blindness phenomenon and with a role for syntactic/semantic factors in the RSVP paradigm.

Results of Abrams, Dyer, and MacKay (1996) with a modified RSVP procedure also support the existence of deep-RD: In their procedure, each RSVP frame contained either a complete phrase,

as in [They wanted][to play sports][but sports][were not allowed], or a non-phrase, as in [They wanted to][play sports but][sports were not][allowed]. Equated on average across the phrase-congruent and phrase-incongruent sentences were the actual words, time per word, frames per sentence, mean words per frame, serial position of pretarget and target words within the frames, and the absolute and relative “eccentricity” of target and pretarget words, i.e., their degree of shift to the left or right of central fixation. The results indicated a significant increase in RB for phrase-incongruent relative to phrase-congruent RSVP sentences, consistent with an effect of syntactic/semantic factors, such that deep-RD decreases or increases in magnitude depending on whether the RSVP procedure makes it easier or more difficult to form word-to-phrase links in sentences. MacKay and Miller (1996) and Miller and MacKay (1996) reported analogous effects for repetition deafness in sentences that are likewise consistent with the existence of semantic blindness and with effects of semantic/syntactic factors on deep-RD.

Conclusion

This study demonstrated age-linked asymmetries predicted under NST between detecting versus retrieving orthographic information. When young and older adults saw briefly presented, high-frequency words that were either correctly- or incorrectly-spelled, their performance on a perceptual task (signaling whether or not the word was misspelled) exhibited two age-linked asymmetries relative to performance on a production task (writing out what they had seen). The Correct Spelling Asymmetry was that older adults perceived correctly-spelled words as correctly spelled as readily as young adults, but were less able to immediately retrieve the correct spelling than young adults. The Misspelling Asymmetry was that older adults detected that a word was misspelled as readily as young adults, but were less able to immediately retrieve the misspelling than young adults. Neither asymmetry was due to artifacts such as task complexity, floor or ceiling effects, general slowing,

stimulus-specific characteristics, sensory-level factors, cohort-related activities, or background characteristics of our participants. In addition, our double dissociation procedures indicated that the Misspelling Asymmetry was specific to aging and required explanation within theories of cognitive aging. Both asymmetries also direct a more general challenge to theories of cognitive aging, namely to explain why some aspects of information processing are more vulnerable to effects of aging than others: Theories that predict either sparing or impairment of verbal abilities across the board in old age are inconsistent with these asymmetries. However, both asymmetries are consistent with NST and with similar age-linked asymmetries that can be discerned in a wide range of other studies that have examined effects of aging independently on the input versus output side of language.

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Appendix: Theory-based Hypotheses and Results Related to Aging and RD

The Binding RD Hypothesis. RD in RSVP sentences has been attributed to a difficulty in rapidly forming the new connections for binding repeated words into phrases for sentence comprehension and recall (see, e.g., Miller & MacKay, 1994, 1996). Because older adults normally require more time than young adults to form new connections, aging should therefore exacerbate the problem that causes RD under this Binding RD hypothesis, and consistent with this prediction, MacKay et al. (1994) showed that older adults exhibit more RD than young adults in recalling RSVP sentences. By analogy, encoding a repeated-letter target in its sequential position in a Type I word in the present orthographic RD paradigm may also require two time-consuming and sequential instances of connection formation from one and the same letter node under the Binding RD hypothesis. Under time pressure, the second repeated-letter, e.g., the added i in hospitable, may therefore become more difficult to bind or encode in its sequential position in hospitable relative to an unrepeated-letter target. By increasing the time required to form new connections, older adults should therefore exhibit greater orthographic RD than young adults under the Binding RD hypothesis. A second prediction is that older adults should retrieve the target letter in the wrong sequential position more often than young adults, and more so for repeated- than unrepeated-letter misspellings because time pressure makes the second of two repeated letters more difficult to encode in its sequential position in a word.

Support for these Binding RD predictions would carry several important implications. One concerns age-linked deficits in the encoding of new information. Unlike the new connections in MacKay et al. (1994) and MacKay and Miller (1996), where a pretarget word becomes linked to its phrase in a sentence, connections representing pretargets in the present paradigm, e.g., the initial (correct) i in hospitable, were formed during childhood, and have received extensive practice over the course of a lifetime. If such highly practiced, existing connections interfere with forming new

connections, e.g., for representing the added *i* and its correct position in hospitable, and if this interference between old and new connections increases with aging, then age-linked deficits in encoding a wide variety of new information (see Burke & MacKay, 1997, for a review) may reflect the fact that older adults have greater knowledge, i.e., more old connections in semantic memory, than young adults.

However, present data supported neither Binding-hypothesis prediction. First, RD was no greater for older than young adults in detecting or in reproducing Type I misspellings. Second, when the target letter was recalled, its position was accurately reproduced no more often for unrepeated- than repeated-letter targets, with a trend in the opposite direction, i.e., fewer positional errors involving repeated- (38%) than unrepeated-targets (45%), for both young and older adults, and age did not interact with position recall, contrary to the Binding RD hypothesis. Additional analyses indicated that none of these contradictory results were attributable to ceiling, floor, or level-of-performance effects, to differences between double conditional, single conditional, and unconditional data, to age-unrelated background characteristics of the participants, or to processes specific to our tasks or stimuli, e.g., error detection based on the abnormal word length of added-letter misspellings.

The contrast between the present results and those of MacKay et al. (1994) using the standard RSVP paradigm for demonstrating RD calls for detailed procedural comparisons between these studies. One problem is that the standard paradigm provides only one type of data: Participants simply recall the RSVP words in the order presented. This makes it impossible to determine whether RD is occurring during perception, or retrieval, or both in this paradigm (see also Fagot & Pashler, 1995; and Hochhaus & Johnston, 1996). The present paradigm clarified this issue by demonstrating that RD is both a perceptual phenomenon (because detection was better for unrepeated- than repeated-letter misspellings) and a retrieval phenomenon (because retrieval was better for unrepeated-

than repeated-letter misspellings). However, neither perceptual RD nor retrieval RD interacted with aging in the present data, ruling out the perception versus retrieval dimension as a viable basis for explaining the differing age effects in MacKay et al. (1994) versus the present study.

Another feature that distinguishes the two paradigms is that the present paradigm presents the repeated elements simultaneously⁵ and in differing spatial positions. However, the standard RSVP paradigm presents the repeated elements sequentially and in the same spatial position, which allows a role for low-level forward and backward visual masking in RD (see MacKay et al., 1996). However, we could think of no reason why reducing forward and backward visual masking effects in the present paradigm would cause the differing age effects between the two studies

In lieu of a methodology-based account, more general accounts of these differing age effects warrant consideration. One is that aging only affects the formation of new connections at phrase levels in unfamiliar sentences, but not the formation of new connections at orthographic levels in familiar words. Another general account that warrants consideration focuses on the theoretical details of how the repeated elements interact to cause RD in the two paradigms. The Binding hypothesis for RD in RSVP sentences postulates an interaction within the system for forming new connections such that two new connections cannot be rapidly formed to link one and the same node representing a repeated word to the two different nodes representing the phrases containing the two repetitions of the word. However, the Binding hypothesis for RD in the present paradigm must postulate an interaction between activating the highly practiced node representing a pretarget letter in a word, e.g., the initial (correct) *i* in hospitable, and the mechanism for forming the new connection to represent the added or target letter *i* in hospitable. Within this more detailed theoretical analysis, aging may only affect the formation of new connections at phrase levels in unfamiliar sentences. Or aging may affect the rapid formation of two new connections from one and the same node, without affecting the

interaction that causes RD in the present paradigm, i.e., activation of a highly practiced node, followed soon after by formation of a new connection involving that same node.

The Inhibition RD Hypothesis. Inhibition is a frequently postulated cause of RD in RSVP sentences, and MacKay (1969) specifically hypothesized a self-inhibition process as the cause of RD in detecting and retrieving repeated-letter misspellings: Under this hypothesis, an activated letter node becomes difficult to activate again for a brief period, so that under time pressure, the second instance of a letter becomes difficult to detect, and if detected, becomes difficult to retrieve during recall. Because older adults suffer from inhibition deficits or age-linked declines in the effectiveness of processes that in theory involve neural inhibition (see Birren & Woodruff, 1983; and Pavlov, as described in McDowd et al., 1995),⁶ the Inhibition RD Hypothesis predicts that young adults should exhibit more RD than older adults. However, present data did not support this Inhibition-hypothesis prediction: RD was no greater for young than older adults in detecting misspellings or in reproducing detected misspellings.

The Refractory Period RD Hypothesis. Slowing of a response to a stimulus due to a prior response to the same stimulus is a type of refractory period that is relatively longer for older than young adults (see Welford, 1977). If this type of refractory period causes RD, then RD should interact with age, repetition, and presentation rate in retrieval, such that older adults experience more RD than young adults at moderate rates, but equivalent RD at fast and at slow rates (see MacKay et al., 1994, for detailed illustration and discussion of these predictions). Present results failed to support these predictions. A 2 (age) x 2 (repetition) x 3 (rate, a three-level factor for young and older adults) MANOVA on the detection data did yield a ***age x repetition x rate interaction** ($p < .033^*$, **should be $p < .046$**), but not the interaction predicted under the Refractory Period hypothesis (i.e., performance was poorer for the middle rate than either the faster or slower rates only for the young participants,

and only for repeated-letter misspellings). No ***other** interactions involving age or rate in these detection data approached significance. Nor did the predicted age x rate interactions appear in double conditional analyses of retrieval. Figure A4 shows the double conditional probability of correctly retrieving repeated- and unrepeated-letter targets as a function of presentation rate for young and older adults, and a 2 (age) x 2 (repetition) x 3 (rate: fast, medium, and slow) MANOVA on these data (excluding 16 young and 20 older adults with empty data cells due to double conditionalization) revealed a main effect of age, $F(1,34)=5.01$, $MSe=.15$, $p < .032$, and of repetition, $F(1,34)=66.21$, $MSe=.11$, $p < .001$, but no main effect of rate, $F < 1$. In addition, although the age x repetition x rate interaction approached significance, $F(2,68)=2.79$, $MSe=.10$, $p < .069$, there were no rate x repetition, age x rate, or age x repetition interactions, all F 's $< 1^7$.

To check whether the extensive data discard in Figure A4 worked against the age x rate interactions predicted under the Refractory Period RD hypothesis, we conducted similar analyses for single conditional data (correct target recall given correct pretarget recall). A 2 (age) x 2(repetition) x 3(rate: fast, medium, and slow) MANOVA on these data indicated a main effect of age, $F(1,67)=7.67$, $MSe=.14$, $p<.007$, with young adults correctly reproducing target letters more often than older adults, and a main effect of repetition, $F(1,67)=264.46$, $MSe=.09$, $p<.001$, with unrepeated-targets reproduced more often than repeated-targets. However, neither the age x rate nor age x rate x repetition interactions were reliable (smallest $p=.21$). These data therefore fail to support the Refractory Period RD hypothesis⁸.

Present results also failed to support the predicted quadratic relation between RD, presentation rate and age, with deviations from linearity in reproducing repeated-targets appearing at a faster rate for young than older adults. For the single conditional data, polynomial trend analyses of RD as a function of rate gave zero-order intercept models as the best fit outcome for both for young and older

adults, with predicted population means (57.3% for young adults, and 41.1% for older adults) that remained constant over the three rates for both young adults ($p < .427$), and older adults ($p < .231$). Mean retrieval of unrepeated-letter targets (75.5% for young adults, and 56.9% for older adults) also remained constant over rate, with a zero-order intercept model as the best fit outcome for both age groups. Finally, retrieval of repeated-letter targets also remained constant over rate, with a zero-order intercept model as the best fit outcome for young adults ($p < .095$), and older adults ($p < .243$). Mean repeated-target retrieval (17.8% for young adults, and 16.8% for older adults) was statistically indistinguishable for the two age groups in this model. In short, our data supported the background assumption or precondition of the Refractory Period RD hypothesis that retrieval is related to presentation time in the same way for young and older adults, but failed to support predictions of this hypothesis: Retrieval of repeated-targets varied linearly rather than quadratically with rate and age, with no age x rate interaction, no repetition x rate interaction, and no age x repetition x rate interaction. Moreover, it seems unlikely that these interactions would have emerged given a wider range of rates. Our range of rates (60ms for young adults, and 100ms for older adults) was comparable to the range in MacKay et al. (1994; 60ms for young adults, and 130ms for older adults) in which the main effect of rate and interactions involving rate were statistically significant. Moreover, adopting faster rates seems likely to cause floor effects in older adults, and adopting slower rates seems likely to cause ceiling effects in young adults (see Figure A4), violating methodological preconditions for between-group comparisons of RD (see the Method section and MacKay et al., 1994).

Perceptual Fusion RD Hypothesis. Perceptual fusion occurs when briefly presented repeated stimuli are perceived as fused, unrepeated, or no different from a continuous stimulus, and according to Kline (1984), stimulus fusion (even for spatially separated stimuli) occurs over longer time periods

for older adults because stimulus traces at all levels of representation persist longer in the aging nervous system. If perceptual fusion causes RD (as suggested, e.g., by Humphreys, Besner, & Quinlan, 1988), so that repeated letters in our briefly presented stimuli are sometimes fused or represented as one in the mind, then Kline's age-linked fusion hypothesis predicts that older adults should fuse repeated letters over longer presentation times than young adults, and age, RD, and presentation rate should interact in the same way as in refractory period accounts of RD.

Consequently, results discussed above that contradict the Refractory Period RD hypothesis also contradict the Perceptual Fusion RD hypothesis. In this regard, it is of interest that results of Hochhaus and Marohn (1991, Experiment 4), MacKay et al. (1994), and MacKay and Miller (1996) also failed to support perceptual fusion accounts of RD. Occurrence of RD in the present retrieval task is also difficult to explain in a purely perceptual account such as the Perceptual Fusion RD hypothesis.

Author Notes

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Footnotes

1. Figure 1 simplifies English orthographic representations for purposes of illustration. For example, the “letter nodes” in Figure 1 represent both letters and letter-locations. Also, a full representation would include a hierarchically organized unit to represent the common English morpheme [-ing].
2. These degrees of freedom reflect the fact that we failed to obtain Nelson-Denny data from two young participants and education data from two older participants. In addition, six older participants did not indicate how many hours/week they spent solving crossword puzzles in the about-to-be described background questionnaire. Finally, we dropped the correctly spelled word judgment from our about-to-be described Type II stimuli because it turned out to have two viable spellings.
3. We conducted single conditional analyses that ignored this condition, with results that indicated dramatic age-linked floor effects. If Figure 3 had presented single conditional probabilities of correct retrieval (i.e., given only correct pretarget recall), these “hidden floor effects” would have led to the erroneous conclusion that young adults exhibit greater retrieval RD than older adults (see Appendix for theoretical implications of this error).
4. A more complex but equally implausible transient error hypothesis can be constructed from two sources. One is the demonstration of Jacoby & Hollingshead (1990) and others that correct spelling exhibits a transient decline for a brief period after reading similar but misspelled words, and the other is the hypothesis of Balota & Ferraro (1993) that general slowing, inhibitory deficits, and age-linked interactions between speed and accuracy may combine in complex ways to cause age-linked but transient errors in speeded response tasks. The MacKay and Abrams (1998) data contradict this more complex transient error hypothesis, as do our analyses of the rate factor (see Appendix). Moreover, an inhibition deficit hypothesis would predict neither the present age x task interactions, nor the comparable age differences in retrieving correctly- and incorrectly-spelled words (see Figure 2).

5. Simultaneous presentation raises the issue of whether ms/letter or ms/word is the most appropriate descriptor for comparing effects of rate in the present study versus other studies. Measured in ms/word, the present 230- to 390ms/word rates are slower than in any previous demonstration of RD: MacKay et al. (1994) showed that young and older adults no longer exhibited RD in the standard RSVP paradigm at rates slower than 210ms/word. However, measured in ms/letter, present rates (about 27-46ms/letter) resemble rates for previous demonstrations of RD (about 27-60ms/phoneme).
6. As Burke (1997) points out, it remains to be shown that age-linked declines in empirical interference effects related to irrelevant information (as in, e.g., Connelly, Hasher, & Zacks, 1991; and Hasher & Zacks, 1988) in principle involve neural inhibition.
7. Close inspection of Figure A4 also illustrates the need for adopting a wide range of rates in assessing the overall effects of aging on RD: Maximal RD occurred at one rate for young adults (230ms/word) and at a different rate for older adults (390ms/word). In addition, although minimal RD may have occurred at the same rate (290ms/word) for young and older adults, retrieval RD at 290ms/word was decreasing with rate for young adults, and increasing with rate for older adults (see Figure A4). These trends suggest that RD could be equivalent, less, or greater for young than older adults at any single, arbitrarily chosen rate.
8. In general, confidence in the meaningfulness of nonsignificant and significant effects reported in the present paper is warranted because following Levin (1997), our design provided sufficient power to detect moderate to large size effects as significant, but not so much power as to render very small effect sizes significant. For example, power computed using Woodward, Bonett, & Brecht (1990) was .82 at $p < .001$ to detect medium effect sizes such as the main effect of age in Figure A4, but power was .36 at $p < .05$ for detecting small effect sizes such as the age x rate x repetition interaction in Figure A4.

Table 1: Background Characteristics of Participants.

	Young Adults		Older Adults	
	M	SD	M	SD
Age*	19.03	1.47	70.33	5.39
Years of Education*	13.03	1.43	16.30	2.32
Health Rating	7.17	2.18	8.13	1.76
Nelson-Denny Vocabulary*	14.68	3.47	20.79	3.07
Digit recall - Forward	7.45	1.24	7.23	1.33
Digit recall - Backward	5.24	1.22	5.35	1.29

*Differences between age groups significant at $p < .05$ or less

Table 2: Summary of Primary and Secondary (RD) Hypotheses, their Predictions, and their Relation to Present Results.

<u>Primary Hypotheses</u>	<u>Predictions</u>	<u>Outcome</u>
Asymmetry Hypothesis	Disproportionately greater effects of aging on production than perception of both correct and incorrect spelling	Supported
Symmetry Hypothesis	Equivalent effects of aging on production and perception of both correct and incorrect spelling	Unsupported
<u>Secondary Hypotheses</u>	<u>Predictions</u>	<u>Outcome</u>
Basic RD Hypotheses	Greater detection and retrieval of unrepeated- than repeated-letter misspellings (double dissociation preconditions)	Supported
Inhibition RD Hypothesis	More RD for young than older adults in detection. More RD for young than older adults in reproducing detected misspellings.	Unsupported
Binding RD Hypothesis	More RD for older than young adults in detecting misspellings and in reproducing detected misspellings. Greater positional uncertainty in retrieval of repeated- than unrepeated-letters, especially for older adults.	Unsupported
Refractory Period RD Hypothesis	An age x repetition x presentation rate interaction, with more RD for older than young adults at moderate rates, but equivalent RD at fast and at slow rates.	Unsupported
Fusion RD Hypothesis	Same as for Refractory Period RD Hypothesis	Unsupported

Table 3: Probability of Correct Detection as a function of Age, Rate, and Spelling Condition for Type I Words.

Spelling Group/Condition	Rate of Presentation (ms/word)									
	230 ms/wd		260 ms/wd		290 ms/wd		340 ms/wd		390 ms/wd	
	Mean	SD	Mean	SD	M	SD	M	SD	M	SD
<u>Young Adults</u>										
Correct Spelling	.922	.129	.861	.178	.922	.138				
Unrepeated-Letter Misspellings	.843	.215	.893	.132	.900	.141				
Repeated-Letter Misspellings	.494	.251	.406	.246	.544	.251				
Repetition Deficit*	.349		.487		.356					
<u>Older Adults</u>										
Correct Spelling					.928	.119	.922	.138	.915	.122
Unrepeated-Letter Misspellings					.839	.268	.835	.201	.860	.208
Repeated-Letter Misspellings					.472	.310	.528	.314	.528	.291
Repetition Deficit*					.367		.394		.387	

*Note: Repetition Deficit(s) are the Unrepeated Condition minus the Repeated Condition

Table 4: Probability of Correct Retrieval as a Function of Age, Rate, and Spelling Condition for Type I Words.

Spelling Group/Condition	Rate of Presentation (ms/word)									
	230 ms/wd		260 ms/wd		290 ms/wd		340 ms/wd		390 ms/wd	
	Mean	SD	Mean	SD	M	SD	M	SD	M	SD
<u>Young Adults</u>										
Correct Spelling	.939	.093	.872	.128	.922	.153				
Unrepeated-Letter Misspellings	.278	.193	.329	.249	.307	.221				
Repeated-Letter Misspellings	.217	.216	.150	.193	.228	.220				
Repetition Deficit*	.061		.179		.079					
<u>Older Adults</u>										
Correct Spelling					.833	.182	.872	.152	.872	.167
Unrepeated-Letter Misspellings					.233	.281	.201	.229	.190	.224
Repeated-Letter Misspellings					.111	.188	.200	.270	.206	.260
Repetition Deficit*					.122		.001		-.016	

*Note: Repetition Deficit(s) are the Unrepeated Condition minus the Repeated Condition

Table 5: Detection Probabilities and Conditional Retrieval Probabilities for All Type II Words and Type II Replacement Misspellings. SDs are in Parentheses.

		Correctly-Spelled Stimuli		Misspelled Stimuli	
		Young	Older	Young	Older
		Adults	Adults	Adults	Adults
All Type II					
Detection	Words	.908	.922	.712	.735
		(.062)	(.060)	(.127)	(.155)
Type II					
Probabilities	Replace- ment	NA	NA	.747	.870
				(.140)	(.104)
Misspellings					
All Type II					
Conditional	Words	.918	.869	.882	.766
		(.071)	(.119)	(.087)	(.185)
Type II					
Retrieval	Replace- ment	NA	NA	.776	.740
				(.680)	(.213)
Misspellings					

Figure Captions

Figure 1: Some of the bi-directional connections in NST for perceiving and producing the visually presented word aging. Also shown is a subset of proposition nodes representing semantic knowledge associated with the concept aging.

Figure 2: Probability of correct detection (left panel) for young and older adults, and conditional probability of correct retrieval given correct perception (right panel) for correctly-spelled and misspelled stimuli.

Figure 3: Probability of correct detection (left panel) for young and older adults, and double conditional probability of correct target-letter retrieval (given correct detection and pretarget recall) for repeated- and unrepeated-letter misspellings (right panel).

Figure A4: Double conditional probability (given correct detection and pretarget recall) of correctly recalling repeated- versus unrepeated-letter targets as a function of presentation rate for young and older adults.