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Adult Age Differences in Knowledge-Driven Reading

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The authors investigated the effects of domain knowledge on online reading among younger and older adults. Individuals were randomly assigned to either a domain-relevant (i.e., high-knowledge) or domain-irrelevant (i.e., low-knowledge) training condition. Two days later, participants read target passages on a computer that drew on information presented in the high-knowledge training session. For both age groups, knowledge improved comprehension and recall and facilitated the processing of topic shifts during reading. In addition, domain knowledge had differential effects on processing across the 2 age groups. Among older (but not younger) readers, domain knowledge increased the time allocated to organization and integration processes (wrap-up) and increased the frequency of knowledge-based inferences during recall. These results suggest that among older readers, domain knowledge engenders an investment of processing resources during reading, which is used to create a more elaborated representation of the situation model.

It is now a commonplace to talk about the demographic shift toward an older population that is unfolding in concert with accelerated change in an information-based economy. In short, life is longer and things are changing faster. As a consequence, the traditional construction of the life span in which education is relegated to youth in preparation for an adulthood of work, citizenship, and leisure is no longer tenable. Rather, education must be integrated throughout the life span to engender both competence and vitality in work and play during adulthood (Riley & Riley, 1994). In spite of this, the empirical study of adult learning, especially as it relates to learning from text, is still in its infancy (Dunlosky & Hertzog, 1998; Smith, 1998). Normative cognitive development in adulthood is often characterized in terms of age-related increases in knowledge stores that co-occur with declines in processing resources (e.g., Baltes, 1997; Salthouse, 1987). However, individuals vary in their trajectories of knowledge growth, individual differences that appear to depend in part on engagement in reading and domain-specific activities (Ackerman & Rolfhus, 1999; Stanovich, West, & Harrison, 1995). On the other hand, the relationship appears to be reciprocal, so that the availability of relevant knowledge can affect cognitive processing during reading, which will give rise to an expanded knowledge network (cf. Feigenbaum, 1989). Because the expanded knowledge base of adulthood is an important asset of this developmental period, some have wondered whether knowledge can offset processing declines in a variety of cognitive arenas (e.g., Arbuckle, Vanderleck, Harsany, & Lapidus, 1990; Clancy & Hoyer, 1994; Hambrick, Salthouse, & Meinz, 1999; Salthouse, Babcock, Skovronek, Mitchell, & Palmon, 1990). Our question was whether older adults take disproportionate advantage of knowledge to support processing during reading.

What Readers Do

Reading processes can be broken down into three general categories: word, textbase, and discourse levels (cf. Stine, Soederberg, & Morrow, 1996; Wingfield & Stine-Morrow, 2000). At the word level, readers identify written symbols (orthographic coding) and the meanings of words (lexical access). At the textbase level, readers instantiate concepts, perform thematic role assignment (i.e., identify predicates and their arguments), and form propositions (idea units). Concepts are both processed immediately (immediacy) and are buffered so that they can be integrated with other concepts within and across sentences. Conceptual integration is a key component of "wrap-up," an increase in reading time at major syntactic constituents such as clause or sentence boundaries (Just & Carpenter, 1980). Wrap-up time is an index of workload in that processing time increases, for example, as the number of new concepts in the text increases (Haberlandt & Graesser 1989;

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Haberlandt, Graesser, Schneider, & Kiely, 1986) and when text ambiguity must be resolved (Daneman & Carpenter, 1983).

At the discourse level, readers go beyond what is explicitly stated in the text (i.e., the textbase representation) to form a representation of the situation described by the text, called a situation model (van Dijk & Kintsch, 1983). This often requires readers to make knowledge-based inferences. Discourse-level processes can involve tracking the spatiotemporal context, goals, and emotional reactions of a protagonist (Soederberg & Stine, 1995; Zwaan, Magliano, & Graesser, 1995). It can also involve attending to the structure of a text. For narratives, structure can take the form of episodes with settings, development, and endings as defined by story grammars (Mandler & Johnson, 1977).

For expository texts, structure can be identified using grammars of exposition, which characterize the explicit and implicit directions given by the writer to develop topics within the texts (Britton, 1994; Meyer & Poon, 2001). In Britton's (1994) system, for example, the creation of expository structure is characterized in terms of argument chains in which readers make implicit online decisions as to whether the author is elaborating on a current topic (e.g., enlarging, expanding, or unitizing; signaled by phrases such as *for example*, *this implies*, and *thus*) or moving on to a new topic (e.g., making connections to an earlier argument or introducing a new subtopic; indicated by phrases such as *another type is*, *however*, and *moving on*). Readers typically slow down when they detect a new topic, particularly when reading text for the first time relative to repeated exposures (Hyönä, 1995).

We used the resource allocation approach (Aaronson & Scarborough, 1976; Haberlandt, 1984; Lorch & Meyers, 1990; Lorch & van den Broek, 1997) to investigate the effects of age and knowledge on reading processes. The underlying assumption of this approach is that each participant's raw reading times can be decomposed into time allotted to constituent reading processes via statistical regression (Lorch & Myers, 1990). For example, by coding each word's length in terms of number of syllables and each word's frequency of occurrence in written text and then regressing reading times onto these features, the resulting regression coefficients represent resource allocation estimates to processes associated with these features, in this example, orthographic coding and lexical access, respectively. Similarly, extra time allocated to the ends of syntactic constituents represents time to consolidate conceptual information within that constituent, and time allocated to clauses introducing a new discourse topic represents the time to establish a new line of argument. This technique allows researchers to characterize the allocation policy to text of individual readers and to assess the self-regulatory shifts in this policy in response to task demands (e.g., Miller & Gagne, in press; Millis, Simon, & tenBroek, 1998; Stine-Morrow, Loveless, & Soederberg, 1996; Stine-Morrow, Miller, & Leno, 2001; Zwaan et al., 1995).

How Knowledge and Aging Affect Text Processing

As is evident from research showing superior reproductive recall among high-knowledge individuals (e.g., Spilich, Vesonder, Chiesi, & Voss, 1979; Voss, Vesonder, & Spilich, 1980), domain knowledge can play an important role in the development of both textbase and situation model representations. Not surprisingly then, research has also shown that knowledge can affect online processing (e.g., Kaakinen, Hyönä, & Keenan, 2003; Miller, Ridolfo, Weisman, & Barshteyn, 2004). For example, prior knowledge can affect lexical access (Miller & Stine-Morrow, 1998) and wrap-up (Miller, 2001, 2003; Miller & Stine-Morrow, 1998; Sharkey & Sharkey, 1987). Knowledge of narrative structure can guide processing (Stine-Morrow et al., 2001). Some evidence suggests that the availability of knowledge affects attention paid to the discourse-level of text processing. For example, Morrow, Altieri, and Leirer (1992) found that experts were less reliant than nonexperts on order of mention (i.e., surface cues) when interpreting pronouns in domain-relevant text. Similarly, Fincher-Kiefer (1992) found that individuals who were knowledgeable about baseball were more likely to activate global inferences while reading baseball texts but less likely to activate inferences to establish local coherence. Thus, the effects of knowledge are evident in online processing in a number of ways.

The strenuous inference generation (SIG) hypothesis states that reading a text about which one already knows something engenders knowledge-based inferences that require additional processing time (Graesser, Haberlandt, & Koizumi, 1987). According to this view, individuals with an existing knowledge base perceive more information in a domain-relevant text than do those without requisite background knowledge because the text acts as a stimulus to activate text-relevant information from the knowledge base. This position implies that high-knowledge individuals require more time to integrate concepts introduced in the text with their prior knowledge. Consequently, the product of this strenuous processing is a text representation in which newly learned concepts are more elaborated and more tightly interconnected with existing knowledge (cf. Mannes, 1994; Mannes & Kintsch, 1987).

This position has support from a number of sources. For example, knowledgeable readers allocate time to global inference generation (Fincher-Kiefer, 1992). Also, response times to a secondary task are slower for high-knowledge relative to low-knowledge readers suggesting that the primary task of reading is more resource consuming when readers possess prior knowledge (Britton & Tesser, 1982). Finally, knowledgeable readers allocate more time to wrap-up when reading texts for which they have prior knowledge relative to low-knowledge individuals (Miller, 2001, 2003). All of these findings suggest that the application of knowledge during reading can require cognitive resources in order to organize and integrate concepts in the text and to draw inferences that allow the high-knowledge reader to map this new information onto existing knowledge structures so as to expand them.

The focus of our study was on how this process changes with age. As noted earlier, given that aging brings declines in mental mechanics but growth in crystallized knowledge (Baltes, 1997), it would be adaptive for older adults to rely more on existing knowledge when they read. This is not unlike some models of early reading in which knowledge compensates for deficits in reading skill (e.g., B. C. Adams, Bell, & Perfetti, 1995) or higher order levels of representation compensate for ineffective lower order processes (Stanovich, 1980). In fact, some data suggest that older adults, relative to the young, rely more on schematic knowledge in a number of domains (see Hess, 1990; Miller & Stine-Morrow, 1998).

In the present study, domain knowledge was randomly assigned to participants through an intensive training session. This allowed us to assess the effects of knowledge in an experimental design, separating out the effects of knowledge from individual differences that give rise to knowledge. Also, in natural knowledge-groups designs, knowledge effects hinge on detecting an interaction between subject group and passage type (i.e., knowledge effects for domain-related passages but not control passages unrelated to the domain of expertise). The experimental approach, however, only requires the use of passages in the targeted domain, and the demonstration of knowledge effects depends on detecting a main effect of group, making it more sensitive to knowledge effects.

We investigated age differences in the effects of knowledge of the heart on online processing of domain-related texts and subsequent memory and comprehension. We were primarily interested in two reading processes that we thought tapped into the consolidation of information that is characteristic of learning: wrap-up and switching to a new topic. If the application of domain knowledge requires an investment of processing resources, as implied by the SIG hypothesis, high-knowledge readers should allocate more resources to these processes when reading domain-relevant texts, relative to low-knowledge readers. Assuming older readers use knowledge to support processing and that declines in mental mechanics make textbase processing more effortful, they should allocate even more time to wrap-up and topic switching in order to form a coherent representation of the text. Finally, we predicted that, as a consequence of this extra processing, high-knowledge individuals would show better comprehension and recall and produce more inferences in the process of retrieval.

Method

Participants

Participants were 42 younger (ages 18–24 years, $M = 19.62$, $SD = 1.61$) and 42 older adults (ages 52–80 years, $M = 67.93$, $SD = 5.35$). The sample was 92.8% Caucasian, 67.9% female, and 42.7% of the sample had 4 years of college or more. Individuals were native speakers of English and were screened for neurological impairments. Younger adults were recruited from introductory psychology courses and from the community, whereas older adults were recruited from alumni records and the community. Younger and older participants did not differ in self-rated health; most individuals rated their health as good or excellent.

To determine whether participants had any prior exposure to the information presented in the target passages, we administered a background questionnaire at the end of the study (so as not to influence performance on the reading task), which probed for education and training experiences relevant to biology in general and the heart in particular. We also asked participants to list any personal experience they had had with heart-related disorders or pathology. All responses for each participant were evaluated by two scorers who then provided a summary rating (yes–no) as to whether the participant had extensive prior relevant knowledge (e.g., a medical degree). Agreement between raters was perfect (100%). Two younger and 3 older adults were deemed to have prior relevant background, and their data were omitted from the study. Additionally, the data from 1 younger adult were removed because of excessively long reading times (6 *SD*s above the mean), and 1 older participant elected to discontinue participation and was replaced. Thus, the final sample consisted of 39 younger and 39 older participants; individuals within age groups were randomly assigned to either a high-knowledge or low-knowledge condition. This resulted in a sample of 20 younger and 20 older high-knowledge participants and 19 younger and 19 older low-knowledge participants.

Participants were administered tests of vocabulary and working memory to determine whether our four groups differed in basic abilities. Vocabulary ability was assessed using the Extended Range Vocabulary Test of the Kit of Factor-Referenced Tests (KFRT; Ekstrom, French, & Harmon, 1976), which is comprised of 40 multiple-choice items requiring individuals to identify synonyms. Working memory was assessed by a composite of reading and listening sentence span tasks (Daneman & Carpenter, 1980; Stine & Hindman, 1994). The sentence spans require individuals to respond *true* or *false* to each sentence in an increasing longer list of sentences that they read (reading span) or hear (listening span). After the list of sentences is presented, individuals say out loud the last word in each sentence. Table 1 contains the means and standard deviations for all individual-difference measures for the four groups.

To determine whether knowledge groups differed in terms of age and whether age–knowledge groups differed in ability, we conduced 2 (age: young, old) $\times$ 2 (knowledge: high, low) analyses of variance (ANOVAs) on age, years of education, and scores on tasks assessing vocabulary and working memory. Neither the knowledge effect on age nor the Age $\times$ Knowledge interaction was significant ($F < 1$ for both). Younger adults had an advantage in terms of working memory capacity, $F(1, 74) = 14.25$, $p < .01$, $MSE = 19.30$, $\eta^2 = .16$. However, older adults had an advantage in terms of years of education, $F(1, 74) = 56.87$, $p < .01$, $MSE = 177.47$, $\eta^2 = .44$, and vocabulary, $F(1, 74) = 121.36$, $p < .01$, $MSE = 4{,}104.62$, $\eta^2 = .62$. Although high-knowledge and low-knowledge groups did not differ in years of education or working memory span ($F < 1$ for both), there was a significant Age $\times$ Knowledge interaction on vocabulary, $F(1, 74) = 5.23$, $p < .05$, $MSE = 176.93$, $\eta^2 = .07$. Despite our randomization procedure, there was a trend for high-knowledge older adults to be higher on vocabulary than low-knowledge older adults, $t(37) = 1.70$, $p < .10$, whereas there was no difference between low- and high-knowledge younger adults, $t(37) = 1.55$, $p > .10$. Therefore, all analyses were conducted with and without vocabulary scores as a covariate. Because

Table 1
Means and Standard Deviations of Individual Difference Measures as a Function of Age and Knowledge

	Young				Old			
	LK		HK		LK		HK	
Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Age	19.10	1.12	19.95	1.93	68.80	6.23	67.26	4.23
Vocabulary	12.53	5.97	10.14	3.14	24.03	6.51	27.67	6.84
Education	13.05	1.19	13.37	1.54	16.38	1.91	16.08	2.26
Working memory span	5.34	1.38	5.30	1.06	4.17	1.22	4.49	0.94

Note. LK = low knowledge; HK = high knowledge.

controlling for vocabulary did not make a substantive difference in the effects of knowledge or Age $\times$ Knowledge interactions, we report the analyses without the covariate, unless otherwise noted.

Materials

Passages. Three expository passages about the heart ("Valves of the Heart," "Generation of the Heartbeat," and "Congenital Defects") were adapted from articles presented in Encarta (Microsoft, 2000), an encyclopedia in CD-ROM format. Texts ranged between 240 and 249 words in length and contained between 101 and 108 propositions (Turner & Greene, 1978) and between 23 and 42 new concepts. Flesch–Kincaid grade level ranged between 9.5 and 12.0.

Comprehension questions. A set of eight true–false comprehension questions was developed for each passage. Half of each set required information that was directly available in the passages and half required inferences to be generated by synthesizing information learned across various statements in the text. Textbase and inference questions were similar in length, with mean word lengths of 12.00 (SD = 3.82) and 12.42 (SD = 3.88), respectively ($t < 1$) and had comparable reliability, with alphas of .35 and .40 for textbase and inference questions, respectively. The correct response for half of each question type for each passage was true.

Procedure

Participants were randomly assigned to one of the two training conditions that differed only in their content domain. Half of the participants learned about the nerve cell and half learned about the heart. Two days later, participants returned for a second session and read passages about the heart. Thus, high-knowledge individuals were those who received training about the heart, and low-knowledge individuals were those who received training about nerve cells. Experimental and control groups were similar in having an intense training session (including a video, written training materials, exercises, a comprehension test, and feedback on performance), time to interact with the experimenter, and exposure to the laboratory setting. The training group differed from the control group only in exposure to the substantive content contained in the target passages. Participants were told that the study focused on how people learn and therefore they would learn about topics within biology using a number of different training formats. Participants were tested individually in sessions that took approximately 2 hr.

Session 1. Participants completed the vocabulary task just prior to beginning the training session. As noted, both knowledge groups participated in identical training exercises except for the content of the domain (heart vs. nerve cell). Training exercises were designed to promote maximum transfer of learning (see Spiro, Vispoel, Schmitz, Samarapungavan, & Boerger, 1987). The tasks approached the content domain from several different angles (e.g., emphasizing structure or process) and utilized several different modalities and training tools (e.g., video, diagrams, texts).

First, participants read the text of, and then watched, a short educational video (roughly 1.5 min in duration for each condition). The video was presented on a computer screen such that participants could repeat it as many times as they wanted. For the high-knowledge group, the video's soundtrack was 177 words in length and showed an animated sequence of how blood flows through the four chambers of the heart. For the low-knowledge group, the length of the soundtrack was 169 words and showed how a signal is transmitted through a neuron to a neighboring neuron. Both groups were then given a supplemental text to study (the high-knowledge version contained 566 words and the low-knowledge version contained 599 words) that provided more detail than the video along with a diagram of the heart or nerve that labeled the important structures. In addition to these study materials, participants were given three exercises (fill-in-the blank, identifying the correct sequence of processes, and labeling structures on a diagram), each of which was administered twice. After the first attempt, individuals were given feedback on their performance and asked to return to the study materials to find the answers to the incomplete and wrong items. Participants were given as much time as they needed to complete the exercises. At the end of the session, a comprehensive short-answer test was administered, and detailed feedback on each response was given such that participants were clear on whether and why they missed a particular item.

Session 2. This session began with a 5-min review of concepts and vocabulary related to the heart. High-knowledge participants were asked to review any or all of the study materials from Session 1 and to do so in any fashion they desired. Because the materials in the first session did not directly deal with information presented in the passages, this review did not serve as an advanced organizer. Because it would have been misleading for the low-knowledge group to spend time reviewing material on the nerve cell, these participants began the session directly with the reading task. Following a practice passage to familiarize participants with the process for reading and assessment of learning, target passages were presented in the same order for all participants in ascending difficulty according to Flesch–Kincaid reading level. Passages were read word by word using the moving-window technique (Just, Carpenter, & Wooley, 1982), such that words appeared on the screen one at a time. When words were not presented, dashes representing each letter were presented along with punctuation marks. Successive button presses caused the next word of text to appear just to the right of the previous word (or at the beginning of a new line) as with free reading. The beginning of a passage was marked with dashes representing the location of words to come, and the end of the passage was marked with *the end* and a cue to recall the passages. Participants were instructed to read at a comfortable rate that would enable them to remember the passages afterwards. After each passage, a prompt appeared asking participants to recall as much of the text as they could out loud. This was recorded for later transcription. After the recall task, comprehension questions were presented on the computer. Prior to the start of this task, participants were asked to place their right and left index fingers on the *true* and *false* keys but were not given instructions regarding the speed with which they should respond.

Following the reading and performance tasks, we administered the background questionnaire and the heart test to ensure that our training was successful. This test consisted of 20 multiple-choice items (with four alternatives) drawing on knowledge of the structure and function of the heart such as, "The valve that connects the left ventricle with the left auricle is called the ______." At the end, participants completed the reading and listening sentence spans.

Results

Manipulation Check

In order to assess the effectiveness of our training program, we entered the total number of correct responses from the heart test into a 2 (age: young, old) $\times$ 2 (knowledge: high, low) ANOVA. A significant main effect of knowledge, $F(1, 74) = 44.26$, $p < .01$, $MSE = 286.29$, $\eta^2 = .34$, confirmed that our training manipulation was successful (low knowledge: M = 12.32, SD = 2.34; high knowledge: M = 16.16, SD = 2.76). There were no age differences in performance on the heart test, $F(1, 74) = 1.11$, $p > .10$, $MSE = 7.17$, $\eta^2 = .02$, and a nonsignificant Age $\times$ Knowledge interaction, $F(1, 74) = 1.30$, $p > .10$, $MSE = 8.40$, $\eta^2 = .02$, showed that the training program was equally effective for both age groups.

Allocation Policy

We analyzed reading times by coding the words in each passage in terms of word, textbase, and discourse-level properties known to affect processing (e.g., number of syllables, word frequency) and then, for each participant, regressing reading times onto these characteristics (Lorch & Myers, 1990). The resulting regression coefficients represent a decomposition of reading time into allocations to particular text processes.

Words were coded 0 or 1 to indicate whether they fell at an intrasentence boundary (e.g., clause, complex noun phrase); the same procedure was used to code sentence boundaries. Following Britton's (1994) grammars of exposition, we coded texts in terms of their topic flow, with clauses as the unit of coding. On the basis of this analysis, words in clauses that introduced a new topic all received 1s and all others received a 0. A number of other text variables were coded to allow us to verify where the effects of knowledge were localized: number of syllables the word contained (orthographic coding), logarithm of the word frequency (lexical access) based on Francis and Kucera (1982) norms, and a dummy code for whether the word represented a new concept (immediacy in conceptual processing). In addition, whether the word fell at the beginning of a new line (time for the reader to scan from the end of the last line to the beginning of the next) and whether the word fell at the beginning of a sentence as well as the serial position of the words within the passage were dummy coded to control these nuisance effects.

Reading times were screened at two levels. Raw reading times were screened for outliers that were greater than an upper limit of 6 *SD*s above the median for each individual. Reading times that exceeded this value were replaced with the upper limit resulting in 1.2% and 1.5% of the data being replaced for low-knowledge and high-knowledge young readers and 2.4% and 2.3% low-knowledge and high-knowledge older readers, respectively (collectively, less than 1.9% of the data points). These trimmed reading times were then regressed onto the array of text characteristics. The resulting regression coefficients were screened for outliers that were 2.5 *SD*s above the mean within age-knowledge groups. Outliers were replaced by the mean for that group. One data point was replaced in each of the high-knowledge young, low-knowledge young, and low-knowledge older groups for the intrasentence and sentence wrap-up measures, and 1 data point was replaced in the high-knowledge young group for the topic shift measure.

Regression coefficients representing time allocated to each of these processes were analyzed in a 2 (age: young, old) × 2 (knowledge: high, low) × 6 (process type: orthographic decoding, lexical access, immediacy of noun concepts, intrasentence wrap-up, sentence wrap-up, topic shift) multivariate analysis of variance. Table 2 contains the means and standard deviations of all resource allocation parameters as a function of age and knowledge. The three-way interaction among age, knowledge, and process type approached significance, $F(5, 70) = 2.17$, $p = .07$, suggesting a trend that was consistent with our predictions that the existence and/or extent of the Age × Knowledge interaction on allocation depended on the particular process. To examine this further, we conducted a series of 2 (age) × 2 (knowledge) ANOVAs on each regression coefficient.

Wrap-up processing. For sentence boundaries, there was a main effect of age, $F(1, 74) = 18.74$, $p < .01$, $MSE = 4{,}657{,}356.50$, $\eta^2 = .20$, showing that older adults allocated more time to wrap-up relative to younger adults. However, neither the knowledge effect nor the Age × Knowledge interaction was significant ($F < 1$ for both).

For intrasentence boundaries, the picture was different. Although the main effect of knowledge was not significant, $F(1, 74) = 1.58$, $p > .10$, $MSE = 9{,}321.69$, $\eta^2 = .02$, the Age × Knowledge interaction was, $F(1, 74) = 6.03$, $p < .05$, $MSE = 35{,}520.22$, $\eta^2 = .08$. This interaction, depicted in Figure 1 (left panel), shows that knowledge increased clausal wrap-up among older adults, $t(37) = 2.03$, $p < .05$, but not among younger adults, $t(37) = 1.49$, $p > .10$. In addition, there was a main effect of age, $F(1, 74) = 19.68$, $p < .01$, $MSE = 115{,}952.35$, $\eta^2 = .21$, indicating that overall, older adults allocated more time than did younger adults to wrap-up at intrasentence boundaries.

Topic shift. Figure 1 (right panel) depicts the effects of knowledge and age on time allocated to set up a new topic. The main effect of knowledge was significant, $F(1, 74) = 5.33$, $p < .05$, $MSE = 23{,}410.12$, $\eta^2 = .07$, indicating that low-knowledge readers required more time to shift to a new topic than did high-knowledge readers. There was a trend for older adults to allocate more time to topic shifts relative to younger adults, $F(1, 74) = 3.71$, $p < .06$, $MSE = 16{,}301.34$, $\eta^2 = .05$. However, the Age × Knowledge interaction was not significant ($F < 1$), indicating that the knowledge effect did not differ across age group.

Word-level processing and immediacy. Knowledge had no effect on word level processing or on immediacy (processing of new nouns; $F < 1$ for both syllables and word frequency), $F(1, 74) = 1.42$, $p > .10$, $MSE = 6{,}879.88$, $\eta^2 = .02$, for immediacy. Nor did age interact with knowledge ($F < 1$ for all three). How-

Table 2
Means and Standard Deviations of Resource Allocation Parameters (Regression Coefficients)

	Young				Old			
	LK		HK		LK		HK	
Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Syllables	34	32	36	46	56	44	62	51
Word frequency (logarithm)	−17	17	−21	8	−35	33	−35	21
New concepts	9	40	12	46	17	98	−24	78
Intrasentence boundary wrap-up	54	51	33	34	89	91	153	108
Sentence boundary wrap-up	298	250	338	395	751	622	864	625
Topic shift	30	30	6	42	70	93	24	79

Note. LK = low knowledge; HK = high knowledge.

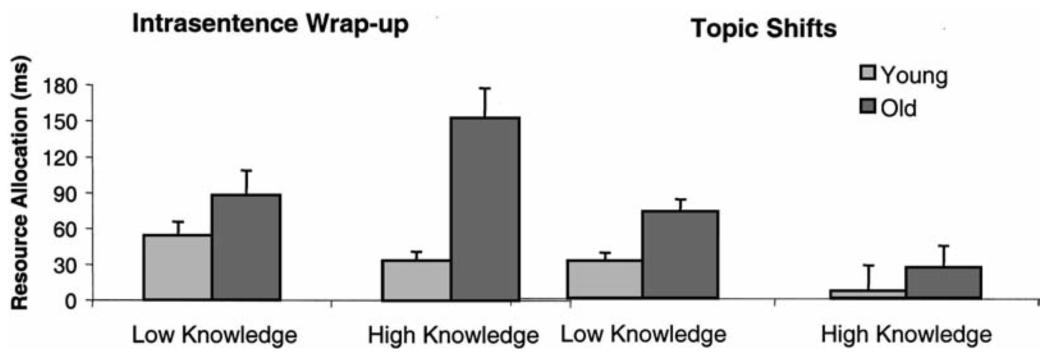

Figure 1. Resource allocation (ms) to wrap-up at intrasentence boundaries (left panel) and topic shifts (right panel) as a function of age and knowledge.

ever, older adults were more facilitated than were younger adults by word frequency, $F(1, 74) = 10.89$, $p < .01$, $MSE = 5{,}071.32$, $\eta^2 = .13$, and older adults spent more time per syllable, $F(1, 74) = 5.58$, $p < .05$, $MSE = 10{,}623.23$, $\eta^2 = .07$.

Performance

Performance was measured in eight ways: textbase and inference comprehension accuracy and latency, textbase recall, elaborative inferences, annotative inferences, and errors. Table 3 contains the means and standard deviations of performance measures as a function of age and knowledge.

Comprehension. The mean proportion correct was calculated separately for textbase and inference questions (out of 12 questions of each type). This proportion as well as mean response time for correct responses were each entered into a 2 (age: young, old) × 2 (knowledge: high, low) × 2 (question type: textbase, inference) repeated-measures ANOVA.

A main effect of question type on comprehension accuracy indicated that textbase questions were easier than inference questions, $F(1, 74) = 25.49$, $p < .01$, $MSE = 0.29$, $\eta^2 = .26$. As expected, there was a main effect of knowledge, $F(1, 74) = 14.85$, $p < .01$, $MSE = 0.45$, $\eta^2 = .17$, such that high-knowledge readers outperformed low-knowledge readers. However, this was qualified by a significant Knowledge × Question Type interaction, $F(1, 74) = 6.13$, $p < .05$, $MSE = 0.07$, $\eta^2 = .08$. High-knowledge individuals scored higher on textbase, $t(76) = 2.06$, $p < .05$, and on inference, $t(76) = 4.71$, $p < .01$, questions relative to low-knowledge individuals. However, as can be seen in the left panel of Figure 2, the greatest benefit of knowledge was for questions that required knowledge-based inferences. Although the main effect of age was nonsignificant ($F < 1$), there was a marginally significant Age × Question Type interaction, $F(1, 74) = 3.94$, $p = .05$, $MSE = 0.04$, $\eta^2 = .05$. As shown in the right panel of Figure 2, there was a trend for younger adults to perform relatively better than the older adults on the textbase questions but for older adults to perform relatively better than the younger adults on the inference questions. Neither the Age × Knowledge interaction nor the Age × Knowledge × Question Type interaction was significant ($F < 1$ for both), indicating that the knowledge effect was constant across age groups and that the Age × Question Type interaction was constant across knowledge groups (see Figure 2).

Table 3
Means and Standard Deviations of Performance Measures as a Function of Age and Knowledge

	Young				Old			
	LK		HK		LK		HK	
Measure	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Comprehension accuracy								
Inference[a]	0.55	0.15	0.70	0.16	0.58	0.16	0.74	0.13
Textbase[a]	0.73	0.14	0.77	0.15	0.67	0.11	0.76	0.16
Comprehension latencies (ms)								
Inference	6,169	1,880	6,363	1,196	6,603	1,635	7,610	2,613
Textbase	5,144	1,157	4,899	732	7,026	2,839	6,588	1,284
Recall								
Textbase[b]	0.18	0.09	0.27	0.11	0.17	0.08	0.24	0.12
Elaborative inferences[c]	0.19	0.10	0.16	0.12	0.38	0.32	0.85	1.24
Errors[c]	0.03	0.03	0.03	0.03	0.05	0.06	0.05	0.05

Note. LK = low knowledge; HK = high knowledge.
[a] Unit of measurement is number of items correct divided by 12 total. [b] Unit of measurement is number of propositions recalled divided by 307 total. [c] Unit of measurement is mean number of inferences (or errors) divided by total number of textbase propositions recalled.

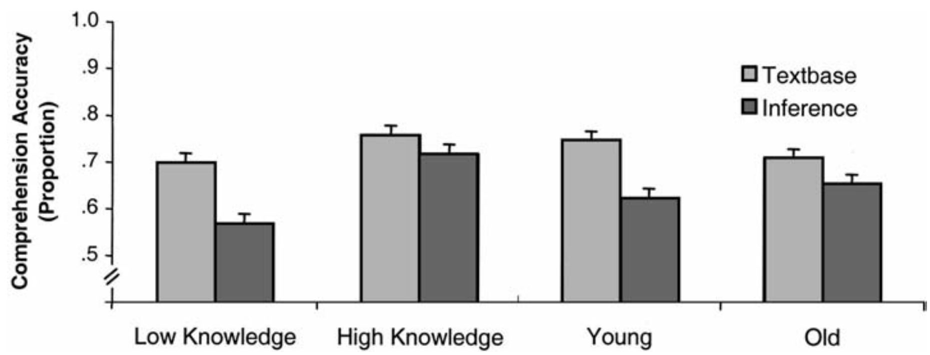

Figure 2. Comprehension accuracy as a function of knowledge and question type (left panel) and age and question type (right panel).

The response times (ms) for correct inference and textbase questions were screened for outliers. Latencies that were greater than 2.5 *SD*s above the mean for each age–knowledge group were replaced by the mean for that group. This resulted in replacement of 2.6% of the data. Cell means can be found in Table 3. Not surprisingly, the ANOVA showed that there was a significant main effect of age on response latencies, $F(1, 74) = 13.70$, $p < .01$, $MSE = 67{,}182{,}506.91$, $\eta^2 = .16$, showing that older adults took longer to respond to questions than did the younger adults. There was a main effect of question type, $F(1, 74) = 14.13$, $p < .01$, $MSE = 23{,}122{,}195.86$, $\eta^2 = .16$, indicating that the requirement to draw an inference increases the latency to answer a question. Although the two types of questions were matched on word length, they were different in content and therefore this main effect should be interpreted with caution. The effect of question type, however, was qualified by a Knowledge × Question Type interaction, $F(1, 74) = 5.23$, $p < .05$, $MSE = 8{,}634{,}255.30$, $\eta^2 = .07$, indicating the question type effect was present among high-knowledge readers, $t(37) = 4.56$, $p < .01$, but not among low-knowledge readers ($t < 1$), an interaction not clearly explicable in terms of content difference of items. In other words, when the reader had background knowledge, the textbase content was relatively more accessible, but there was more to do in computing inferences, resulting in relatively longer response times in the inference condition. This effect did not vary with age, as shown by a nonsignificant Age × Knowledge × Question Type interaction, $F(1, 74) = 1.50$, $p > .10$, $MSE = 2{,}468{,}686.53$, $\eta^2 = .02$. Remaining effects (knowledge and Age × Knowledge) were nonsignificant ($F < 1$ for both).

Recall. Recall protocols were scored for four types of information: textbase recall, elaborative inferences, annotative inferences, and errors. Textbase recall was scored as the proportion of idea units recalled across the three textbases (out of 307 possible propositions) using a gist-based method of scoring based on Turner and Greene (1978). Reliability was assessed by having 20% of the recall protocols scored by a second rater. The correlation between the two sets of scores was .97. Elaborative inferences were correct additions to recall of the textbase. Annotative inferences were additions that related the textbase to personal experience or described a personal reaction to the information (Gould, Trevithick, & Dixon, 1991). Errors were incorrect recall of the textbase or incorrect elaborative inferences. Each of these measures was analyzed separately in a 2 (age: young, old) × 2 (knowledge: high, low) ANOVA.

There was a main effect of knowledge on textbase recall, $F(1, 74) = 12.38$, $p < .01$, $MSE = 0.12$, $\eta^2 = .14$, such that high-knowledge individuals recalled more propositions than did low-knowledge individuals. The knowledge effect was comparable for younger and older adults ($F < 1$ for the interaction), and on average, young and older adults recalled similar amounts of the textbase ($F < 1$; see Table 3 for cell means).

Recall was scored as an elaborative inference if it represented an accurate expansion of the textbase. For example, an elaborative inference may relate textbase information to previously learned material (including that learned in Session 1 training or a previous passage) or may be in the form of a metaphor that further described or clarified concepts in the passage. Elaborative inferences were quantified by counting the idea units in each correct elaborative statement using the same gist criterion used to score the textbase recall. An example of a correct elaborative inference would be a statement that the pericardium is *heart tissue*. Although the passage mentioned the use of the pericardium to repair heart defects, it did not explicitly state that it is tissue or that it comes from the heart. Therefore, the idea units (REF PERICARDIUM TISSUE) and (MOD HEART TISSUE) were counted as elaborative inferences. The number of inferential idea units across the three passages divided by the total textbase recall was the dependent variable. There was a main effect of age such that older adults' protocols contained more elaborative inferences relative to total recall than did younger adults' protocols, $F(1, 74) = 9.24$, $p < .01$, $MSE = 3.77$, $\eta^2 = .11$. Although the main effect of knowledge was nonsignificant, $F(1, 74) = 2.34$, $p > .10$, $MSE = .95$, $\eta^2 = .03$, the Age × Knowledge interaction was marginally significant, $F(1, 74) = 3.04$, $p < .09$, $MSE = 1.24$, $\eta^2 = .04$. Inspection of the cell means (see Table 3) indicates that the knowledge effect was greater among older adults. This effect became significant when vocabulary was controlled, $F(1, 73) = 4.03$, $p < .05$, $MSE = 1.63$, $\eta^2 = .05$.

Recall was scored as an annotative inference if it related information recalled from the textbase to personal experience or described a personal reaction to the information. For example, during recall of a passage about the valves of the heart (including the mitral valve), 1 participant stated, "In fact, somebody was talking to me on the telephone yesterday and said that [she] had her mitral valve replaced." There were only four examples of such chains of annotative inferences, all of which were from the older sample. Two of these were from the high-knowledge condition and two were from the low-knowledge condition.

Recall was scored as an error when participants recalled the textbase inaccurately or made an incorrect elaborative inference. Errors were quantified by counting the number of idea units in the statement that made it incorrect (errors of commission) or, conversely, the idea units that were missing that were necessary to make the statement correct (errors of omission). For example, one participant recalled, "The sound of the heart is produced by the heart itself, not by the valves" when the original passage stated that the sound of the heart is *not* produced by the heart muscle itself, but *is* produced by the closing of the valves. There were two incorrect propositions in this statement; omission of (NOT [MAKE HEART SOUND]) and inclusion of (NOT [MAKE VALVE SOUND]). The dependent variable was the number of incorrect idea units across the three passages as a proportion of total textbase recall. Although older adults made more errors than did younger adults, $F(1, 74) = 5.10$, $p < .05$, $MSE = 0.01$, $\eta^2 = .06$, knowledge did not help to reduce the number of errors made ($F < 1$). The Age × Knowledge interaction was also nonsignificant ($F < 1$).

Discussion

The Integration of Knowledge Can Require Cognitive Effort

In the present study, we found partial support for the notion that domain knowledge evokes SIG. Older readers (but not younger readers) allocated additional time to conceptual organization and integration processes when applying knowledge, implying that knowledge application during learning can be effortful (see also Miller, 2001). When knowledgeable older adults read texts that contained novel concepts related to their recently acquired knowledge base, they allocated more time to activate the complex network of existing connections and to establish new connections. To take a concrete example, individuals who had learned about the heart were aware that the semilunar valves snap shut immediately after the ventricles contract, preventing blood from flowing back into the heart. Later, all participants read that the second part of the heartbeat sound is created by the snapping shut of the semilunar valves. However, the high-knowledge participants were able to use the information they learned earlier to make the connection that the second sound of the heartbeat occurs just after the ventricles contract. These types of connections provide an enriched conceptual network of the heart.

Further support for the SIG hypothesis was evident in the data on comprehension latencies. Among young and older knowledgeable readers, correct inference questions required more time than did textbase questions. Low-knowledge readers, of course, also had lower accuracy in answering these questions than did high-knowledge readers. In fact, their accuracy was very close to chance (57% ± 2), suggesting that their correct answers may have been, in part, due to guessing. High-knowledge readers, on the other hand, had higher levels of performance (72% ± 2). The achievement of correct answers among this group apparently entailed a more thorough analysis, presumably driven by their more extensive knowledge of the topic. Thus, these data suggest that effort is required to make inferences about concepts embedded in a rich knowledge base.

For example, after reading the passage about the generation of the heartbeat, both high- and low-knowledge readers were equally fast to verify that Pukinje fibers conduct impulses relatively quickly through the heart, a statement that was simply stated in the textbase. However, high-knowledge readers took a relatively long time to correctly verify the inference that the sinoatrial node could be considered the heart's pacemaker. The text stated that electrical impulses are initiated and synchronized by this node. The low-knowledge readers were less successful in correctly endorsing this statement (probably in part because they were less able to retrieve the relevant textbase information, as shown by the accuracy data), but when they were successful, this judgment may have been based on a fairly superficial analysis of *initiation and synchrony* being synonymous with *pacemaker*. High-knowledge readers, on the other hand, who were more likely to retrieve relevant textbase information, as well as prior related knowledge such as where this node is located and the sequence of events that comprise one heart beat, had more information at hand to evaluate in considering the aptness of this metaphor. They were more likely to be correct, but it took them longer.

Although conceptual integration and inference generation appear to be strenuous when readers have background knowledge, topic shifts appear to be easier with background knowledge. Construction of an online representation of expository text has been characterized as following the implicit "instructions" of the author for creating a structure (Britton, 1994, p. 641; see also Meyer & Poon, 2001). The reading time data provide some support for this conceptualization in showing that readers slowed down when a new line of argument was established by the author. The data from the present study suggest that following the structure provided by the writer or speaker is relatively automatic when relevant knowledge is available. Facilitation of topic shifts among high-knowledge readers is inconsistent with the SIG hypothesis. It is not clear why knowledge can exaggerate wrap-up allocation but facilitate the processing of topic shifts, but we speculate that this difference might be due to the extent to which these two processes are obligatory. Because the discourse signals constituting instructions to establish a new thread to an argument are not necessarily domain specific, both low- and high-knowledge readers attempt to comply with the author's request. In the absence of background knowledge to support and guide the construction of these new threads or frameworks (Gernsbacher, 1996), readers struggle to construct the representation requested by the author. High-knowledge readers, on the other hand, have a more developed conceptual network that facilitates the establishment of these new threads. Conceptual elaboration at wrap-up, however, does not occur as an obligatory response to the author's request, but rather as a function of whether there are links to be made. Low-knowledge readers, in a sense, simply do not know there is more to do, whereas high-knowledge readers have an array of concepts available that invite elaboration and integration.

Our findings align with other work on knowledge. McNamara and colleagues (McNamara, Kintsch, Songer, & Kintsch, 1996; McNamara & Kintsch, 1996), for example, assessed the effects of knowledge and text structure on comprehension performance. They found that, among knowledgeable readers, minimally coherent texts lead to greater gains in performance on tasks requiring a situation model representation. For low-knowledge readers, coherent texts were more beneficial. The researchers also measured word reading times and found that high-knowledge individuals spent more time reading low-coherence texts relative to low-knowledge individuals, suggesting that these texts engendered strenuous processing among high-knowledge readers. Our data also suggest that readers can be encouraged to apply their knowledge to moderately difficult scientific texts. However, other research has not shown the effects of knowledge on reading times. Rawson and Kintsch (2002) found that individuals who were given relevant background information had higher free recall relative to those who were not given this information but that both groups spent similar amounts of time reading texts. However, they measured total reading time across a set of texts. Thus, knowledge may affect encoding in very specific ways, for example, with qualitative shifts in processing effort that may not be measurable as effort at a gross level.

Does knowledge always increase the effort required for learning? Probably not. When one is reading about something that one knows well, so that the new material fits well within existing knowledge schemas, the reverse may be true. In this case, knowledge structures become readily accessible during reading (Bransford & Johnson, 1972), enabling automatic processing with very few cognitive resources (cf. Klein, 1993). For example, Sharkey and Sharkey (1987) gave readers short passages to read that either evoked or did not evoke a script, such as going to a restaurant. They found that individuals spent less time reading words at sentence-boundary locations when they could use a script to guide processing. These data suggest that schematic, or script-based, knowledge reduces the demands of conceptual integration (see also Miller & Stine-Morrow, 1998). Similarly, McNamara and Kintsch (1996) showed that although high-knowledge adults read low-coherence texts more slowly than did low-knowledge adults, they read high-coherence texts more quickly. That pattern is consistent with the notion that the ease with which knowledge can be applied during reading will depend on the fit between the text and the reader's prior knowledge. Although this remains to be directly tested, we speculate that whether knowledge facilitates conceptual processing or exaggerates inference-based resource demands will depend on the degree of conceptual overlap and organizational congruence between existing knowledge and the text that is encountered.

Age Differences in Knowledge Use

The data from the present study also provided some support for the notion that older readers are knowledge driven. This is consistent with earlier data, showing an exaggerated effect of schematic knowledge for older readers (Miller et al., 2004; Miller & Stine-Morrow, 1998). However, older readers allocated more time to conceptual organization and integration when applying domain knowledge relative to when they read information for which they had little relevant knowledge (Miller, 2001). In an age-comparative study, Miller (2003) showed that younger and older experts showed similar increases in wrap-up when reading texts in their domain of expertise. Because knowledge was experimentally manipulated in the present study, these data build on this work by showing that knowledge effects were not due to selection differences. Although younger adults in Miller (2003) increased resource allocation when reading domain-related texts but did not in the present study, the earlier study assessed knowledge that had been acquired over years rather than days. Presumably that study required readers to apply an extensive knowledge base, requiring many new connections to be made, and this was effortful for both younger and older adults. In the present study, younger adults did not appear to be challenged by newly acquired knowledge perhaps because there are fewer connections to be made. Older adults appear to increase effort when applying knowledge regardless of how established or extensive the knowledge is.

The strenuous nature of conceptual integration to some extent appeared to pay off for older adults. Older adults with background knowledge were relatively more likely to make elaborative inferences during recall. Thus, older adults were more likely to go beyond the literal textbase and accurately apply what they had learned during recall. Older adults in general also did relatively better on the inference relative to textbase comprehension questions. These findings are consistent with research showing that, relative to younger adults, older adults are more interpretive and less literal in their recall style (C. Adams, 1991; C. Adams, Smith, Nyquist, & Perlmutter, 1997) and attend more to the situation model level of representation than to the textbase (Radvansky, Zwaan, Curiel, & Copeland, 2001; Stine-Morrow, Gagne, Morrow, & DeWall, in press; Stine-Morrow, Morrow, & Leno, 2002).

Educational implications for these findings are twofold. First, older learners are often characterized as slower. Our data suggest that the more extensive knowledge base of older adults (Ackerman & Rolfus, 1999) may engender a greater level of processing effort that is productive in building knowledge. Thus, being relatively slower in learning may not be a mark of inefficiency but rather of active reflection that constitutes true learning. Second, the absence of the knowledge effect among the young suggests that active integration with existing knowledge may be a more fragile self-regulatory process among young learners, though certainly not entirely absent (e.g., Mannes, 1994). This suggests that teachers may need to provide more active encouragement and environmental support to encourage these strategies among young adult learners.

In summary, the current study provides support for the notion that among older adults the use of knowledge can be strenuous, at least during conceptual integration, and this effort can pay off in the capacity of productive elaborations of material. These findings are interesting in light of the fact that older adults experience declines in mental mechanics but increases in crystallized knowledge. Conceptual integration is presumably a resource-consuming process (Smiler, Gagne, & Stine-Morrow, 2003) that is related to memory performance (Stine-Morrow, Milinder, Pullara, & Herman, 2001). Our findings suggest that crystallized knowledge may augment this aspect of mental mechanics among older readers. To the extent that attentional allocation is generally enhanced by knowledge among older readers, this may be an important mechanism underlying selective optimization (Baltes, 1997), a developmental process wherein the probability of successful aging is enhanced by focusing limited resources toward growth.

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