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When learning about a single topic in natural reading environments, readers are confronted with multiple sources varying in the type and amount of information. In this situation, readers are free to adaptively respond to the constraints of the environment (e.g., through selection of resources and time allocation for study), but there may be costs of exploring and switching between sources (e.g., disruption of attention, opportunity costs for study). From an ecological perspective, such properties of the environment are expected to influence learning strategies. In the current study, we used a novel reading paradigm to investigate age differences in the effects of information richness (i.e., sentence elaboration) and costs of switching between texts (i.e., time delay) on selection of sources and study time allocation. Consistent with the ecological view, participants progressed from less informative to more informative texts. Furthermore, increased switch cost led to a tendency to allocate more effort to easier materials and to greater persistence in reading, which in turn, led to better memory in both immediate and delayed recall. Older adults showed larger effects of switch cost, such that the age difference in delayed recall was eliminated in the high switch cost condition. Based on an ecological paradigm of reading that affords choice and self-regulation, our study provided evidence for preservation with age in the ability to adapt to changing learning environments so as to improve performance.

Keywords: cognitive aging, information foraging, self-regulated learning, text memory

Reading is a critical activity throughout the life span, and is a positive predictor of cognitive resilience in later adulthood (Manly, Schupf, Tang, & Stern, 2005). People read for many reasons, including for pleasure, as well as to learn new things. With the rise of electronic media, the ecology of literacy is showing dramatic change. Given the vast array of information sources available in these new ecologies, the learner must make choices about how to allocate effort. For example, suppose a person is planning a trip to a new city and wants to learn about the place in advance. A search on the Internet would likely yield multiple texts on the history, points of interest, local culture, and so forth. Because it is unrealistic to learn all the information, the individual must make decisions about which texts to read and in what order, how long to spend with each one, and when to move on to another. These decisions are likely based on many factors, including the amount of information in the source, the ease of accessing sources, the amount of time available, and the capacities of the learner. In this circumstance, because the individual can control his or her learning process, he or she is engaged in the process of self-regulated learning. In the dominant paradigm for investigating text memory, passages are presented under controlled conditions, so that less is known about how people learn when they can freely select and allocate time to multiple texts. Furthermore, while the existence of adult age differences in reading comprehension and memory for text is well established, little is known about how younger and old adults manage learning in environments that afford such self-regulation. Thus, using a novel paradigm, our goal of the current study was to investigate age-related changes in how individuals learn information in interactive reading environments.

Cognitive Aging and Reading

Age differences favoring the young are the norm in both text memory (Johnson, 2003) and in processing efficiency, as measured by the time required to encode ideas (Hartley, Stojack, Mushaney, Annon, & Lee, 1994; Stine & Hindman, 1994). However, age differences are moderated by a number of factors.

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For example, older readers may benefit from self-pacing. Based on a meta-analysis of the text memory literature, Johnson (2003) concluded that age differences are generally smaller when readers can control the pace of text presentation. However, this is not always the case. Even though older readers require more time to encode ideas from text as a consequence of working memory declines (Hartley et al., 1994; Stine & Hindman, 1994), they do not always allocate sufficient time, which can contribute to poorer memory performance (Ratner, Schell, Crimmins, Mittelman, & Baldinelli, 1987; Stine-Morrow, Miller, & Hertzog, 2006). However, this has been shown in the context of studies in which participants are asked to remember the content of the particular texts they are given and in which they have little choice in selection. Relatively less is known about how aging impacts the ability to regulate learning when multiple texts are available.

Self-Regulated Learning

In self-regulated learning (SRL), individuals actively take control of and evaluate their own learning and behaviors (Zimmerman, 2001). To self-regulate, learners need to monitor the effectiveness of their learning strategies and respond to the feedback generated from monitoring in various ways, such as changing study strategies. Theories of SRL predict how people select items, allocate study time, and decide when to stop studying.

Metacognitive Approaches

Metacognitive approaches examine self-regulation by focusing on the relationships between the perceived state of learning (typically measured as rated judgments of learning) and the desired level of learning, which will influence study strategies. The two most prominent theories are the Discrepancy Reduction (DR) model (Dunlosky & Thiede, 1998; Nelson & Narens, 1990) and the Region of Proximal Learning (RPL) model (Metcalfe, 2002).

The DR model argues that learners allocate effort to reduce the discrepancy between the perceived current knowledge level and desired knowledge level. From the DR model perspective, because the discrepancy between the current learning state and the desired learning state is greater for the difficult or less-well learned items than the easy or well-learned items, learners will allocate more attention to the more difficult items by selecting them more often and spending more time studying them (Thiede & Dunlosky, 1999). Both younger and older adults have been found to allocate more time to items judged to be less well-learned on earlier study trials (Dunlosky & Hertzog, 1997), though older adults' use of the DR heuristic may be reduced compared with younger adults, as suggested by a weaker relationship between judgments of learning and allocation of study time (Dunlosky & Connor, 1997).

According to the RPL model (Metcalfe, 2002), people allocate effort to a region in which learning is perceived to be neither too easy nor too hard. Items that are already mastered and items that are too difficult are not good candidates for learning because investing time and effort into them produces less return in learning new information and may create an opportunity cost through neglect of unlearned items that are more tractable. Thus, the model predicts that learners select the least difficult items among the ones that are currently unknown, and then shift progressively to more difficult items (Metcalfe & Kornell, 2003; Son & Metcalfe, 2000). The model also suggests that people will differentially allocate study time to the easy items because they have the highest expected rate of return on the investment of effort.

Older adults appear to use an RPL heuristic at least as well as their younger counterparts. No obvious age differences are typically found in selection strategy, such that both younger and older learners choose to study items from simple to difficult (Price, Hertzog, & Dunlosky, 2010; Price & Murray, 2012). However, older adults may allocate study time differentially to easier items compared with younger learners (Miles & Stine-Morrow, 2004; Price & Murray, 2012), suggesting a tendency to rely more on an RPL strategy.

Ecological Approaches

Ecological approaches to the study of self-regulated learning focus on the ways in which learners adapt to the constraints of the environment in which information is contained. A fundamental assumption of ecological approaches is that the ways in which learning is managed are grounded in more primitive mechanisms that evolved to enhance survival (Hills, 2006; Hills & Hertwig, 2011; Metcalfe & Jacobs, 2010). For example, Pirolli and Card (1999) suggested that humans actively search and gather information for learning, decision-making and problem solving, based on more primitive adaptations that evolved for food foraging in the wild. According to their information foraging (IF) model, certain properties of food foraging can be applied to how humans search for information. For instance, information is distributed in the environment much in the way that food is distributed in the wild, in clusters or "patches." Patches can vary in the amount of resources they contain (i.e., energy or information) and how easy these resources are to extract. Resources available in the patch are finite and unknown before the patch is actually exploited, or consumed, but there may be "scent cues" that provide hints on the potential gain from the patches. A general assumption is that with more time spent in exploiting a patch, the rate of gain (i.e., the uptake of energy or information) decelerates because of the limited nature of the resources within the patch and/or the capacities of the organism.

Like an animal foraging for food in the wild, human foragers must trade off between exploitation of a particular patch and exploration for others. The amount of information that can be gained from a single source is finite, because of the nature of the source, the learner, and/or an interaction between the two. Consequently, foragers switch to new sources when the rate of gain diminishes to some critical point. In fact, when human foragers are given a choice about how to manage multiple tasks, they tend to interleave them rather than performing them serially, even though there is some cost to do so (Payne, Duggan, & Neth, 2007).

Within this framework, questions of interest include what the optimum strategies are for exploration and exploitation and how/why individuals deviate from what is optimal. Optimal foraging theory (Stephens & Krebs, 1986) describes the heuristics that animals use to balance the gain from exploitation within a food patch and the costs of exploration (moving between patches) in the wild to find new patches. Based on this work, Pirolli and Card (1999) presented a model of information foraging that makes predictions about how learners should adapt to the constraints of the learning environment to maximize the amount of information extracted. As noted above, it is assumed that a patch has diminishing returns in the cumulative amount of information gain as a function of exploitation time within a patch. In other words, as

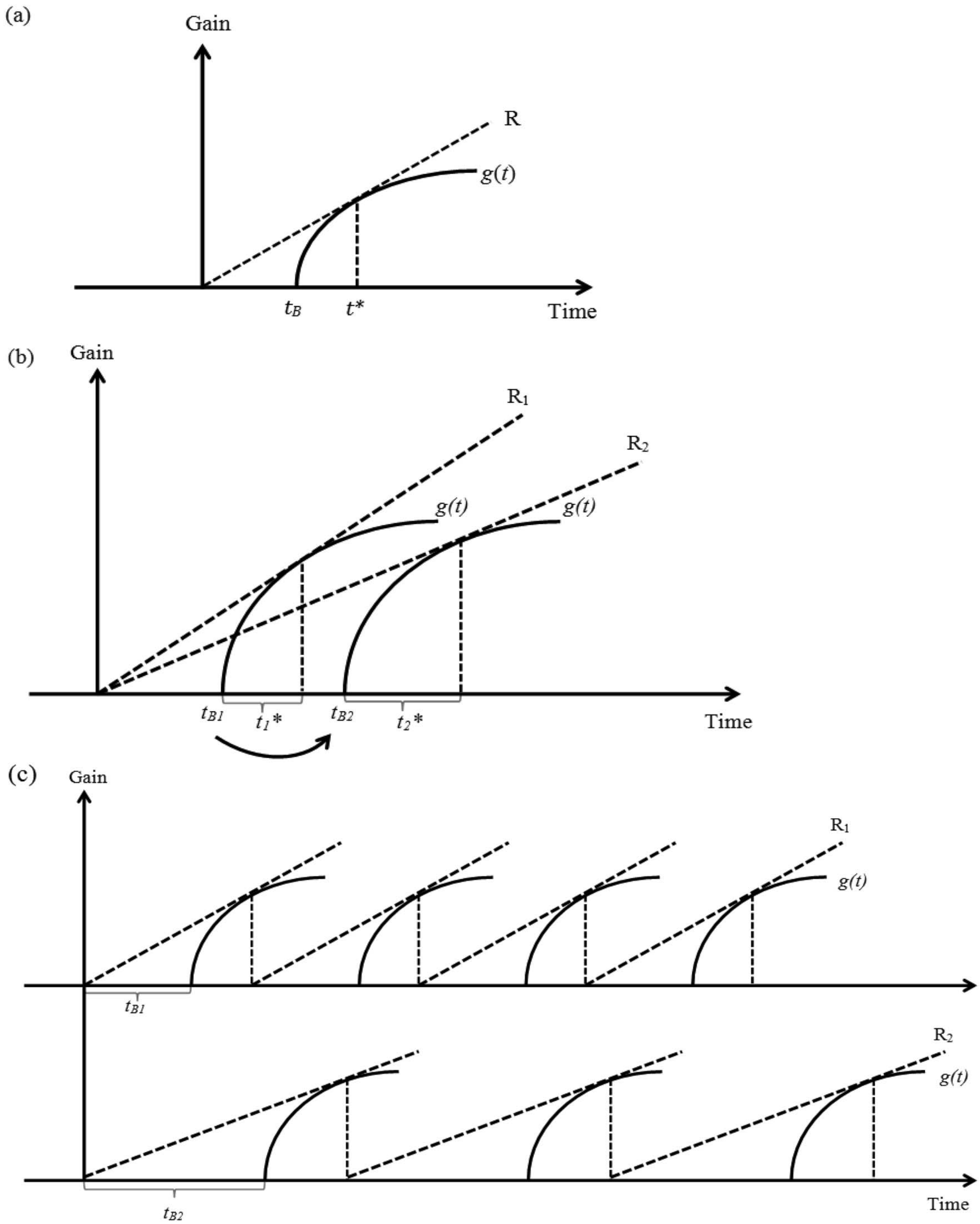

Figure 1. Graphical representation of how switch cost between information sources affects optimal persistence time, according to Foraging Theory. (a) Assuming that t_B is the average travel time between sources, the optimal time, t^*, within a source is when the marginal value of gain within the source is equal to the average rate of gain for the whole environment, R. Leaving before this point, the forager learns less than optimal given the travel time to the next patch; leaving after this point, the forager is "laboring in vain" (Nelson & Leonesio, 1988) and would be likely to learn more by taking advantage of the accelerated uptake of a new source. (b) Assuming a consistent rate of gain across patches in the ecology, as the travel time increases from t_{B1} to t_{B2}, the average rate of gain decreases from R_1 to R_2. To improve the overall outcome with t_{B2}, it would be better to persevere in the current patch for a longer time before moving on to a new patch (i.e., the optimal within-patch time increases from t_1^* to t_2^*). (c) Assuming time in the environment is held constant, the overall effect of an ecology with high switch costs, relative to one with low switch costs, will be reduced information gain, but optimal performance relative to the particular ecology depends on increased time allocation to the source as switch cost increases.

time increases, the rate of gain decelerates, so that the slope of the within-patch gain function (i.e., $g(t)$ in Figure 1a) decreases. Assuming that the human forager's goal is to maximize acquired knowledge, Charnov's (1976) marginal value theorem holds that the optimal forager should remain in a patch only so long as long as the rate of marginal gain at any given point in time is greater than the average rate of gain in the environment. As illustrated in Figure 1a, as soon as the rate of marginal gain equals the average rate of gain, the forager should stop exploiting the current patch and switch to another patch to optimize overall gain. As shown in Figures 1b and 1c, the greater the travel time between patches in the ecology, the more persistence is required within particular patches to achieve optimal information gain in that ecology. In fact, there is evidence suggesting that switch cost can increase within-patch perseverance. Dennis and Taylor (2006) found that when people read information on a browser for a decision-making task, longer time delays between browsing pages led to longer time spent within a page and less switching between pages. While such data cannot speak to whether information foragers achieve true "optimality," the implication is that they to some extent adapt to the constraints of the environment in a way that moves performance toward optimal levels.

Foragers also make decisions on which particular patches they select and the order in which they are selected. Such decisions are based on information scent cues that can inform the value or potential gain of the patches (Fu & Pirolli, 2007), operationalized as a title, key words, or surface characteristics of the text. Foragers take into account the size of the prey: either too small or too large will cost more energy than can be consumed, so foragers prioritize patches that are "just right."

There is some overlap between metacognitive and ecological approaches. For example, Metcalfe and Jacobs (2010) have argued that the RPL strategy is analogous to this "Goldilocks" foraging principle. As a research paradigm, the ecological approach can be distinguished by the focus on behavioral adaptation in environments with different properties (without necessarily measuring metacognitive judgments, which have the drawback of potentially altering the behavior; Stine-Morrow, Shake et al., 2006).

There is growing interest in ecological perspectives for understanding cognitive aging (Mata & von Helversen, 2015; Mata, Wilke, & Czienskowski, 2009, 2013; Stine-Morrow, 2015). For example, Chin, Payne, Fu, Morrow, and Stine-Morrow (2015) used a word search puzzle task to examine age differences in information foraging. Younger and older adults were asked to maximize the number of words found in a set of puzzles. Older adults switched fewer times among puzzles and also spent more time on a puzzle without finding a word before switching to another puzzle. These findings implied that compared with younger adults, older adults were less explorative in search and were more likely to persevere within patches past the optimal point. Similar age differences have been found in studies using virtual fishing and anagram tasks (Mata et al., 2009, 2013). However, age differences in information foraging have not been studied in reading.

The Current Research

The purpose of the current study was to examine age differences in selection, time allocation, and memory in a self-regulated reading environment. A reading task was designed to simulate learning in electronic environments, in which readers can freely explore texts for learning. Texts varied in the amount of content from very short "factoids" to more detailed descriptions, and cues for text elaboration (i.e., scent cues) were available at selection. Between-patch switch cost was operationalized as a time delay after selecting a text. Our interest was two-fold.

First, we were interested in testing an implication of the IF model that, to the extent that foragers make adaptations toward optimality, increased switch cost will increase persistence in learning. This is a somewhat unintuitive idea that is not predicted by metacognitive theories of SRL, and provides an opportunity to test a unique implication from the fundamental mechanisms of ecological theory in a learning context. Given that older adults' poorer text recall is sometimes attributable to underallocation of effort (cf. Stine-Morrow, Miller, et al., 2006), IF offers an interesting avenue to increase perseverance—with possible memory-enhancing effects. Recall that Chin et al. (2015) found that older adults persisted past an optimal point in a task that involved search for discrete items. Encoding ideas during reading, on the other hand, involves a more working memory demanding process (Daneman & Merikle, 1996), and this demand in the long run may lead to a decrease in persistence, especially for older adults (cf. Hess, 2014). Our question was whether older adults might be differentially affected by switch cost, in this case, to an advantage.

Second, we were interested in how adults varying in age would manage a text environment in which sources varied in information richness. The ecological view (e.g., Metcalfe & Jacobs, 2010) suggests that learners will prioritize relatively easier items for study. For example, learners would be expected to select the less informative sentences first, and to generally avoid the most complex items, while the DR model predicts that learners will select the more complex sentences first because they are more information-rich. There is some evidence for the prioritization of easier items among younger, middle-aged, and older learners (e.g., Price et al., 2012), but this idea has not been examined with text materials. A further implication of the ecological view is that the prioritization of easier materials should be exaggerated by switch cost in increasing the press for more efficient learning. To the extent that older adults' reduced resources would make such adaptations more important, it might be expected that older adults would show an exaggeration of this effect.

Method

Participants

Participants were 24 younger (18–35 years of age), 24 middle-aged (40–54 years of age), and 24 older (61–81 years of age) community-dwelling adults. All individuals were native speakers of English and were screened for severe neurological or medical conditions, such as Parkinson's, Alzheimer's disease, and stroke. Older adults were also screened for mild cognitive impairment with the Montreal Cognitive Assessment (MoCA $\geq$26; Nasreddine et al., 2005). As shown in Table 1, age groups did not differ in education, or in vocabulary, as measured by the Advanced Vocabulary Test (Ekstrom, French, & Harmon, 1976). Younger adults showed higher levels of speed of processing (Salthouse, 1991) and verbal working memory (Stine & Hindman, 1994), whereas

Table 1
Means (SEs) of Sample Characteristics of Young, Middle-Aged, and Older Adults

Variable	Young (N = 24)	Middle-aged (N = 24)	Older (N = 24)	F(2, 69)	p value
Age	24.08 (.97)	47.56 (.96)	68.96 (1.13)		
Education	15.71 (.35)	15.46 (.49)	15.06 (.35)	.65	ns
Vocabulary	16.89 (1.23)	18.38 (1.53)	20.31 (1.27)	1.61	ns
Speed	.64 (.15)	.07 (.17)	−.71 (.12)	21.01	<.001
WM	4.58 (.26)	4.02 (.16)	3.65 (.18)	5.24	.01
PE	5.42 (.61)	10.62 (.94)	10.33 (.82)	13.42	<.001

Note. WM = working memory; PE = print exposure; speed scores were obtained from averaging the z-scores from Letter and Pattern Comparison Tasks; ns. = not significant.

middle-aged and older adults demonstrated a higher level of print exposure (PE) based on the Author Recognition Test (Stanovich & West, 1989), indicating they were more experienced readers than younger adults.

Materials

Reading materials consisted of 21 factual sentences about Connecticut (CT) and 21 about Rhode Island (RI), adapted from the stimuli used by Shake, Noh, and Stine-Morrow (2009). The sentences were all related to CT or RI, but otherwise, there was minimal content overlap among them. The sentences varied in the number of propositions or "idea units" (defined in terms of the network of relationships between concepts; Kintsch & van Dijk, 1978), such that there were three elaboration conditions, low, medium, and high, containing 2–4, 6–8, and 10–12 propositions, respectively, with seven sentences per condition for each state. Sample sentences are shown in the Table 2.

Items in the two material sets did not differ in the number of propositions (M_{CT} = 7.14, SE = 0.75; M_{RI} = 6.81, SE = 0.71), number of syllables (M_{CT} = 32.19, SE = 3.53; M_{RI} = 31.57, SE = 3.22), or number of new concepts (M_{CT} = 6.76, SE = 0.63; M_{RI} = 6.57, SE = 0.69), $t(40) = .32$, $p = .75$, $t(40) = .13$, $p = .90$, and $t(46) = .20$, $p = .84$, respectively. Furthermore, there were no State × Elaboration interactions, all $F(2, 36) < 1$.

Design

The experiment was conducted in two blocks, a low switch cost block and a high switch cost block, the order of which was counterbalanced across subjects. Sentences about CT or RI were presented together in a block, with materials counterbalanced across switch cost condition, resulting in four stimulus lists. Preliminary analyses showed that the order of the switch cost block presentation and the materials had no effects on the participants' behaviors, $ps > .10$, so we report analyses collapsed across block. The experiment followed a 3 × 2 × 3 mixed factorial design with one between-subjects variable, age (young vs. middle-aged vs. old), and two within-subject variables, switch cost (SC; small vs. large) and sentence elaboration (low vs. medium vs. high). Switch cost was manipulated by introducing a random loading time after the selection of a sentence (i.e., 0–2 and 6–8 sec in the small- and large-SC conditions, respectively). Sentence elaboration varied within each block.

Table 2
Sample Reading Materials for Connecticut

Elaboration level	Sample sentence
Low	Samuel Colt was a gunsmith from Connecticut.
Medium	The cathedral of St. Joseph in Hartford is noted for its carillon bells, as well as 24 spectacular stained-glass windows that line the nave.
High	For 17 years, Mark Twain occupied a peach-colored Victorian Gothic house in Hartford, which is now open to the public and features personal items including an oak mantel brought back from Scotland.

Procedure

The testing session took about 1.5 hr. Participants were first administered the Advanced Vocabulary Test, and Letter and Pattern Comparison Tasks to assess processing speed, followed by the reading task on iPad.

During the reading task, participants sat in front of an iPad set up in portrait orientation. The task was programmed on a second-generation iPad, and sentences were presented in Calibri 18-point font. Participants were told that their task was to learn about different areas of the country by reading a series of short passages. They would take a quiz after they learned about each state, but in preparation for the quiz, they were to recall aloud as much information as they remembered immediately after reading each passage. They were told that the texts about each area were single sentences that varied in the amount of information. Participants selected passages one at a time by pressing a button on the iPad screen, in which each button corresponded to one sentence. The buttons were of three sizes corresponding to elaboration level.

As illustrated in Figure 2, participants entered the selection page and saw 21 buttons representing the set of texts available. Once participants selected a text, the screen momentarily turned gray with an animated spinning wheel in the center. From the participant's perspective, this was the result of the iPad loading the sentence, however, the duration of "loading" was the manipulated variable for SC. Participants could read as long as they wanted before pressing a red button on the screen to indicate that they were ready to recall. The signal to recall the sentence was the appearance of a question mark, which appeared immediately after the button press. An audio recording of recall was saved by the iPad. Participants were asked to recall as much of the information from the text as they could, but told that there was no need to use

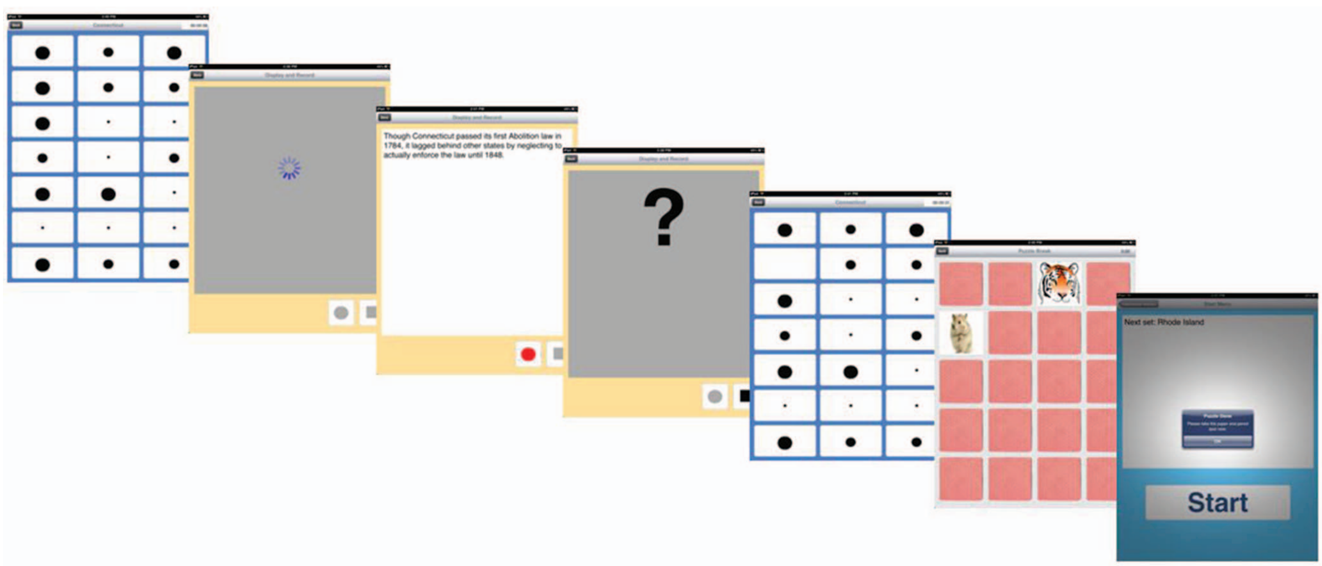

Figure 2. Illustration of the sequence of events in the reading task on the electronic tablet. See the online article for the color version of this figure.

the exact words of the original text. When participants were done with the recall, they terminated the recording by pressing a black button, which returned them back to the selection page. Participants did not have the option to restudy the sentences, therefore, once a sentence had been selected, the corresponding button disappeared from the selection page. There was a time limit of 11 min for each topic.[1] Loading time (i.e., switch cost) and time spent on immediate recall were also counted in the time limit. Participants were told to use as much of the time as they needed to learn about the state. When participants finished learning, they played a card matching game on the iPad as a distractor task before a delayed cued recall quiz. The time spent on the distractor task was at least 90 s, but when participants did not use all 11 min for study, this extra time was added to the card matching game, so that the time from beginning study for the block to delayed cued recall was controlled across subjects.[2] The delayed cued recall task was a fill-in-the-blank task, in which 1 to 4 words in each sentence were replaced with a single blank. Each blank in the delayed cued recall task was worth two points, and partial credit was awarded. The maximum raw score was 42 if a participant read all the sentences for a state. Participants first practiced this reading task with three sentences about Louisiana in the three elaboration conditions.

Note that because the study time limit was the same in both SC conditions, participants had less time to study in the large SC condition compared with the small SC condition. To contextualize the difference, if a participant read all of the sentences, the functional time available was 10.65 min in the small SC condition, and 8.55 min in the large SC condition.

Lastly, participants were administered the reading span task and the Author Recognition Test. Participants were also asked about their previous experience with RI or CT; no one indicated familiarity with this content, so no one was excluded from the analysis. Participants were also asked about whether they noticed the differences in the loading time of the passages. Three quarters of the participants did ($n = 54$), but only seven participants (<10%) noticed that the loading time differed between blocks; most participants incorrectly thought that it was the longer texts that took more time to load.[3] Of those who reported noticing the variations among loading times, the longer loading time was rated as being less acceptable, $t(53) = 4.53$, $p < .001$ and more annoying, $t(53) = 4.10$, $p < .001$, than the shorter loading time, supporting the idea that the loading time did incur some cost.

Results

Unless otherwise specified, data were analyzed with a 3 (Age) × 2 (Switch Cost) × 3 (Elaboration) repeated measures analysis of variance (ANOVA), and only statistically significant results are reported. Results were reported with Greenhouse-Geisser correction on degrees of freedom, when Mauchly's test indicated that the assumption of sphericity was violated.

[1] A pilot experiment was conducted with similar reading materials, but 24 sentences about each topic and unlimited study time. Among the five younger and four older adults who elected to read all of the texts, the total time on reading and immediate recalling ranged from 8.5 to 19.1 min ($M = 13.1$, $SE = 0.65$). Therefore, the time limit of 11 min was chosen for this experiment to accommodate to the relatively smaller material set and to ensure that participants could read most of texts.

[2] In the small-switch-cost condition, 17 younger, 16 middle-aged, and 14 older adults finished learning all the sentences before the timer ran out, which was 65.3% of the total sample. Whereas in the large-switch-cost condition, 9 younger, 11 middle-aged adults, and only 1 older adult finished earlier than the time limit, which was 29.2% of the participants.

[3] There were no age differences in noticing the loading time. Furthermore, whether or not noticing the loading time did not impact participants' item selection, reading time allocation, or recall performance. We concluded that self-reported loading time reflected a subjective perception that did not directly influence actual reading behaviors of participants.

Item Selection Behaviors

Of the 42 sentences available, younger adults selected 39.2 on average (range: 28–42), middle-aged adults selected 38.7 (range: 28–42), and older adults selected 37.8 (range: 31–42). The age differences were not significant, $F(2, 69) < 1$.

To examine the pattern of sentence selection based upon text elaboration, we followed the procedure used by Metcalfe and Kornell (2005) by assigning each sentence a numerical value representing its level of elaboration (1, 2, and 3, for low, medium, and high, respectively). Because all participants read at least 12 of the sentences in each block, only the first 12 sentences selected were included in the analysis of selection behaviors. The 12 sentences were grouped into four groups of three for the analysis of elaboration ranking as a function of Switch Cost, Order, and Age. As shown in Figure 3, there was a main effect of Order, $F(1.8, 125) = 11.84$, $p < .001$, $\eta_p^2 = .15$, indicating that participants selected shorter and easier sentences first before moving to more complex sentences. This pattern was consistent with predictions from IF and RPL (Price et al., 2010; Price & Murray, 2012), and suggested that participants selected items for which they were able to manage the difficulty. Although there was a numerical trend for middle-aged adults to give priority to relatively more complex materials, the age by order interaction was not significant, $F(3.6, 125) < 1$. Nor did selection vary with switch cost, $F(3, 207) < 1.9$.

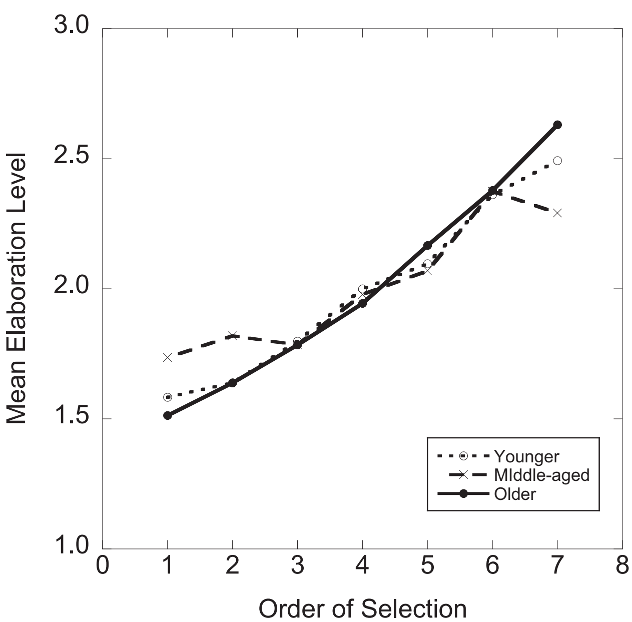

Figure 3. Mean elaboration level of younger, middle-aged, and older readers' sentence selections, collapsed across switch-cost conditions. Each order position represents the average of three text selections. The analysis of variance (ANOVA) reported in the text is based on Orders 1 to 4, for which complete data were available for all participants. Participants who selected at least 19 of the 21 items are included in the data points for all 7 points on the *x*-axis. At the 5th selection, $N_M = 23$; at the 6th selection, $N_Y = N_M = 22$, $N_O = 21$; at 7th selection, $N_Y = 16$, $N_M = 15$, $N_O = 10$; otherwise, $N_Y = N_M = N_O = 24$. Age differences were not significant at any of the ordinal positions of selection, *F*s < 1.

Reading Time

Mean sentence reading time for the three age groups as a function of elaboration and switch-cost conditions is reported in seconds in Table 3, and the effect of switch cost on sentence reading time for each age group is plotted in Figure 4 (upper panel). The age difference was significant, $F(2, 69) = 4.20$, $p = .02$, $\eta_p^2 = .11$, with post hoc analyses indicating that older adults spent more time in reading a single sentence than the other age groups, $p < .05$, whereas the younger and middle-aged adults did not differ, $p > .05$. Trivially, reading time increased with sentence elaboration level (because of length), $F(1.2, 81.6) = 251.21$, $p < .001$, $\eta_p^2 = .78$.

The main effect of switch cost was significant, $M_{SMALL} = 11.04$, $SE = 0.37$; $M_{LARGE} = 11.70$, $SE = 0.42$, $F(1, 69) = 7.22$, $p = .01$, $\eta_p^2 = .10$, indicating that participants allocated more time to reading when switch cost was large compared with when it was small. Indeed, large switch cost led to numerically longer reading times for all three age groups and in all three elaboration conditions (cf. Table 3). There was a numerical trend for older adults to show a larger effect of switch cost: switch cost effect approached significance for the older group, $F(1, 23) = 4.14$, $p = .053$, $\eta_p^2 = .15$, but not for the other two age groups, $p > .15$. The Switch Cost by Age interaction did not reach significance, $F(2, 69) < 1.3$, so these age differences in the effect are to be interpreted cautiously. In any case, within an IF framework, the results clearly showed that readers adapted to the increased switch cost with greater persistence in reading, which suggests a shift in strategy toward optimality. Older adults were at least as sensitive to switch cost, if not more so, relative to the younger and middle-aged adults.

Immediate Recall

Immediate recall was transcribed and then scored based on the propositional units, with an interrater reliability of .95. Figure 4 (middle panel) shows the mean proportion of propositions recalled from sentences that were selected. The main effect of Age was significant, $M_Y = .82$, $SE = 0.02$, $M_M = .78$, $SE = 0.02$, $M_O = .71$, $SE = 0.02$, $F(2, 69) = 9.81$, $p < .001$, $\eta_p^2 = .22$, with post hoc analyses showing that older adults recalled fewer ideas than the other two age groups, $p < .05$, and that middle-aged adults did not differ from the young, $p > .1$. Participants showed better recall performance when sentences were embedded in ecologies with large switch costs ($M_{LARGE} = .79$, $SE = 0.01$) than with small switch costs ($M_{SMALL} = .75$, $SE = 0.02$), $F(1, 69) = 8.32$, $p = .005$, $\eta_p^2 = .11$. Consistent with the IF model, increased switch cost promoted not only time allocation, but also better memory, implying that the adaptation in strategy improved information gain. Again, there was a numerical trend for older adults to show a larger effect of switch cost on recall, but the switch cost effect did not vary with Age, $F < 1$.

Finally, there was a main effect of Elaboration, $M_{LOW} = .93$, $SE = 0.01$, $M_{MED} = .75$, $SE = 0.01$, $M_{HI} = .63$, $SE = 0.01$, $F(1.7, 115) = 439.07$, $p < .001$, $\eta_p^2 = .86$, such that less of the information was recalled as elaboration level increased. This Elaboration effect varied with age in an Age × Elaboration interaction, $F(3.4, 115) = 3.01$, $p = .03$, $\eta_p^2 = .08$, such that recall performance of the older adults was more compromised than that of the younger and middle-aged adults as the sentence elaboration level increased ($M_{Y\_LOW} = .96$, $M_{Y\_MED} = .80$, $M_{Y\_HI} = .69$; $M_{M\_LOW} = .93$,

Table 3
Mean Reading Time (Seconds) as a Function of Sentence Elaboration and Age in the Small- and Large-Switch-Cost Condition

Age group	Switch Cost:	Elaboration condition: Low		Medium		High		Overall	
		Small	Large	Small	Large	Small	Large	Small	Large
Younger		5.44 (.26)	5.55 (.31)	10.64 (.73)	11.45 (.85)	14.23 (1.17)	14.29 (1.25)	10.10 (.64)	10.43 (.73)
Middle		5.71 (.26)	5.88 (.31)	11.86 (.73)	12.05 (.85)	14.56 (1.17)	15.35 (1.25)	10.71 (.64)	11.09 (.73)
Older		5.91 (.26)	7.12 (.31)	13.24 (.73)	14.63 (.85)	17.77 (1.17)	18.44 (1.25)	12.30 (.64)	13.40 (.73)
Overall		5.68 (.15)	6.18 (.18)	11.91 (.42)	12.71 (.49)	15.52 (.67)	16.03 (.72)		

M_{M_MED} = .75, M_{M_HI} = .65; M_{O_LOW} = .90, M_{O_MED} = .69, M_{O_HI} = .56).

Effective Reading Time

Older adults spent more time reading the sentences, but recalled less, particularly for high elaboration sentences, suggesting that they may have been persisting past an optimal point for sentences with more information (cf. Jarvstad, Rushton, Warren, & Hahn, 2012; Payne et al., 2007). To examine the efficiency of information gain, we analyzed effective reading time, time per proposition recalled (i.e., the time required to encode a single idea). As shown in Figure 5, the main effects of age, $F(2, 69) = 3.96$, $p < .001$, $\eta_p^2 = .29$ (Y = M < O, based on post hoc tests), and elaboration, $F(1.4, 97) = 6.77$, $p = .005$, $\eta_p^2 = .09$ (L < M = H), were significant. Importantly, older adults were, in fact, relatively less efficient in encoding ideas from medium and high elaboration sentences, $F(2.8, 97) = 3.46$, $p = .022$, $\eta_p^2 = .09$. Switch cost did not impact efficiency of encoding ideas, $F < 1$.

Delayed Cued Recall

Interrater reliability of scoring for delayed recall was .98. We calculated the conditional delayed recall for each participant based only on the sentences that were selected. These data are plotted in Figure 4 (bottom panel). The benefit of Switch Cost observed in immediate recall was sustained in delayed cued recall, $F(1, 69) = 15.11$, $p < .001$, $\eta_p^2 = .18$ ($M_{SMALL} = .59$, $SE = 0.02$; $M_{LARGE} = .66$, $SE = 0.02$). While the main effect of age was not significant, $F(2, 69) = 1.63$, $p > .2$, there was a marginally significant interaction between Age and Switch Cost, $F(2, 69) = 2.96$, $p = .06$, $\eta_p^2 = .08$. Post hoc tests indicated that older adults retained more information from reading texts in the large SC condition than in the small SC condition, $t(23) = 4.07$, $p < .001$, whereas Switch Cost had no effect on recall in the younger and middle-aged groups (ts < 1.3). An interesting find was that the age effect on recall was significant when switch cost was small, $F(2, 69) = 3.39$, $p = .04$, but it was eliminated when the switch cost was large, $F(2, 69) < 1$.

Finally, there was a main effect of Elaboration, $F(1.7, 114) = 8.17$, $p = .001$, $\eta_p^2 = .11$, indicating that participants retained relatively better memory of high elaborative sentences than low and medium elaborative sentences ($M_{LOW} = .60$, $SE = 0.02$; $M_{MED} = .61$, $SE = 0.02$; $M_{HI} = 0.67$, $SE = 0.02$). The effect of elaboration did not vary with Age, $F(4, 138) < 1$.

Adaptation in the Reading Ecology

Because readers had a fixed time limit within which to explore and select items for reading and recall, there is a rich opportunity in this paradigm for understanding how readers regulate effort in the ecology as a whole. In this section, we report analyses that exploit these opportunities.

Earlier, we reported the proportion of propositions recalled from the sentences that were selected. Given the goal of the task, to learn as much information about the whole topic as possible, the total number of propositions recalled in immediate recall can be taken to reflect the total amount of information "consumed." The age difference in total propositions recalled was significant, $F(2, 69) = 10.47$, $p < .001$, patterning with the analysis of proportion recall ($M_Y = 205$, $SE = 5$; $M_M = 193$, $SE = 7$; $M_O = 167$, $SE = 6$; Y = M > O). The difference in functional time available between the small and large SC conditions did not allow us to meaningfully examine how switch cost impacted the total information immediately recalled. However, assuming that small and large SC conditions each constituted certain amounts of time in which to work, we could examine how that time was distributed across elaboration conditions and the consequent distribution of ideas recalled. In particular, we were interested in whether participants changed their time allocation strategy across texts varying in elaboration with a change in the search environment. Specifically, we wondered whether a greater switch cost would lead to a greater effort allocated toward easier materials.

In the left panel of Figure 6 is plotted the proportion of total time allocated to reading sentences from the three elaboration levels in each SC condition. A main effect of Elaboration, $M_{LOW} = .19$, $SE = 0.01$, $M_{MED} = .39$, $SE = 0.01$, $M_{HI} = .42$, $SE = 0.01$, $F(1.3, 92.4) = 264.94$, $p < .001$, $\eta_p^2 = .79$, supported the observation that the proportion of time allocated to low-elaboration sentences was significantly smaller than in both the medium-, $t(71) = 29.06$, $p < .001$, and the high-elaboration condition, $t(71) = 21.37$, $p < .001$. Note that, even though the high-elaboration texts at an individual level took longer to read, in the overall task readers spent as much time with the texts of intermediate difficulty as they did with the most complex texts. Importantly, the effect of Elaboration was moderated by Switch Cost, $F(1.3, 92.3) = 7.53$, $p = .004$, $\eta_p^2 = .10$. When switch cost was large, participants allocated more time to reading medium-, $t(71) = 2.21$, $p = .03$, and low-, $t(71) = 1.88$, $p = .06$, elaboration texts, but less time to high-elaboration texts, $t(71) = 3.21$, $p = .002$. This interaction suggested that participants adapted to the larger switch cost by allocating more of their

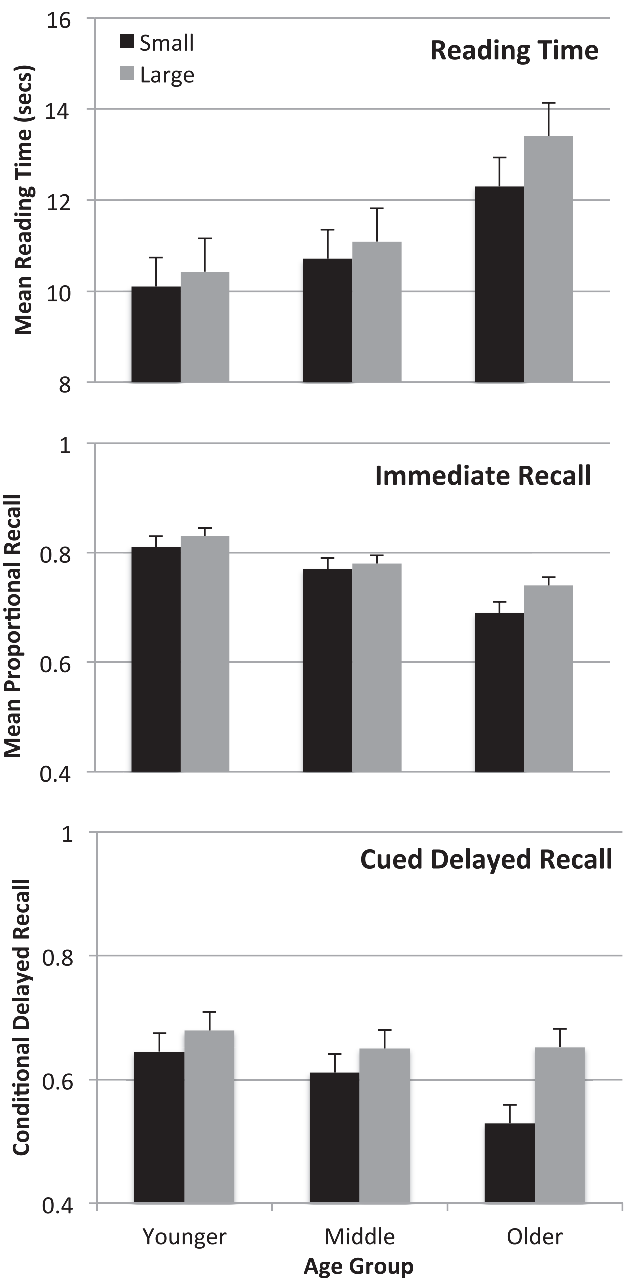

Figure 4. Mean reading time, proportional immediate recall, and conditional delayed cued recall as a function of age for small and large switch cost conditions. *SE*s are represented by vertical bars.

effort to simpler texts. This shift from high-elaboration to low- and medium-elaboration texts with switch cost was exaggerated for older readers, as shown in a three-way interaction among Age, Elaboration, and Switch cost, $F(2.7, 92.3) = 3.16$, $p = .03$, $\eta_p^2 = .08$.

Similar to the analysis on the proportion of total reading time, the proportion of total propositions of immediate recall from the three elaboration levels was calculated in each switch-cost condition. As shown in the right panel of Figure 6, the pattern of results was the same as the one found in proportion reading time, with a main effect of Elaboration, $M_{LOW} = .20$, $SE = 0.004$, $M_{MED} = .38$, $SE = 0.01$, $M_{HI} = .42$, $SE = 0.01$, $F(1.2, 82.6) = 209.52$, $p < .001$, $\eta_p^2 = .75$, a two-way interaction between Switch Cost and Elaboration, $F(1.6, 108) = 9.31$, $p = .001$, $\eta_p^2 = .12$, and also a three-way interaction, $F(3.1, 108) = 2.94$, $p = .03$, $\eta_p^2 = .08$. These results showed that particularly for older adults, more ideas were recalled from simpler texts under the large switch cost compared with the small cost condition. Collectively, these findings suggest that older readers were more likely to adapt their reading strategy according to the properties of the reading ecology compared with their younger and middle-aged counterparts.

Finally, we were interested in whether the better recall performance with high SC was related to the increased reading time engendered by high SC. To explore this relationship, we computed an index for each participant reflecting the change in persistence across switch condition by subtracting the mean sentence reading time under the small switch cost condition from the mean under the large switch cost condition. Similarly, the improved immediate and delayed recall scores were calculated by subtracting the recall scores (i.e., both the proportion of propositions recalled from sentences for immediate recall, and the conditional delayed recall) under the small switch cost condition from the large switch cost condition. There was a significant positive correlation between the increase in reading time and the increase in immediate recall, $r = .41$, $p < .001$, as well as between increases in reading time and delayed recall, $r = .33$, $p = .005$. These findings suggested that the more readers adapted to the switch cost with perseverance, the more information they retained.

Given that adults were found to benefit more from the large switch cost in delayed recall (and the effects tended that way in reading time and immediate recall), we were curious as to whether the relationships between increased persistence and improved memory performance were stronger among older adults. Only among older adults was the correlation between increased persistence and increased immediate recall significant, $r_O = .67$, $p < .001$ ($r_Y = .12$, $r_M = .26$; based on an r-to-z transformation, this correlation among older adults was stronger

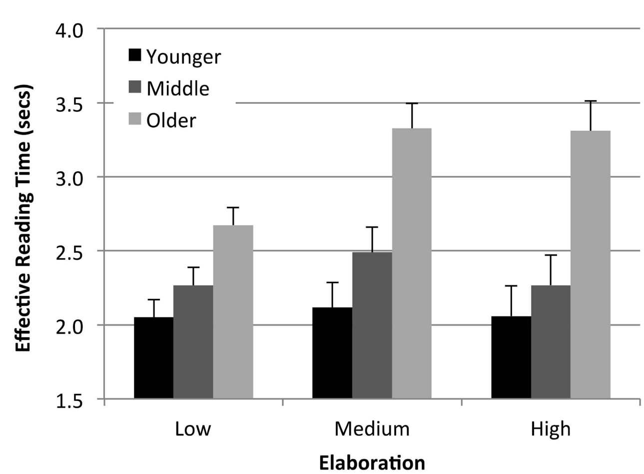

Figure 5. Effective reading time as a function of age and sentence elaboration level. *SE* is represented by vertical bars.

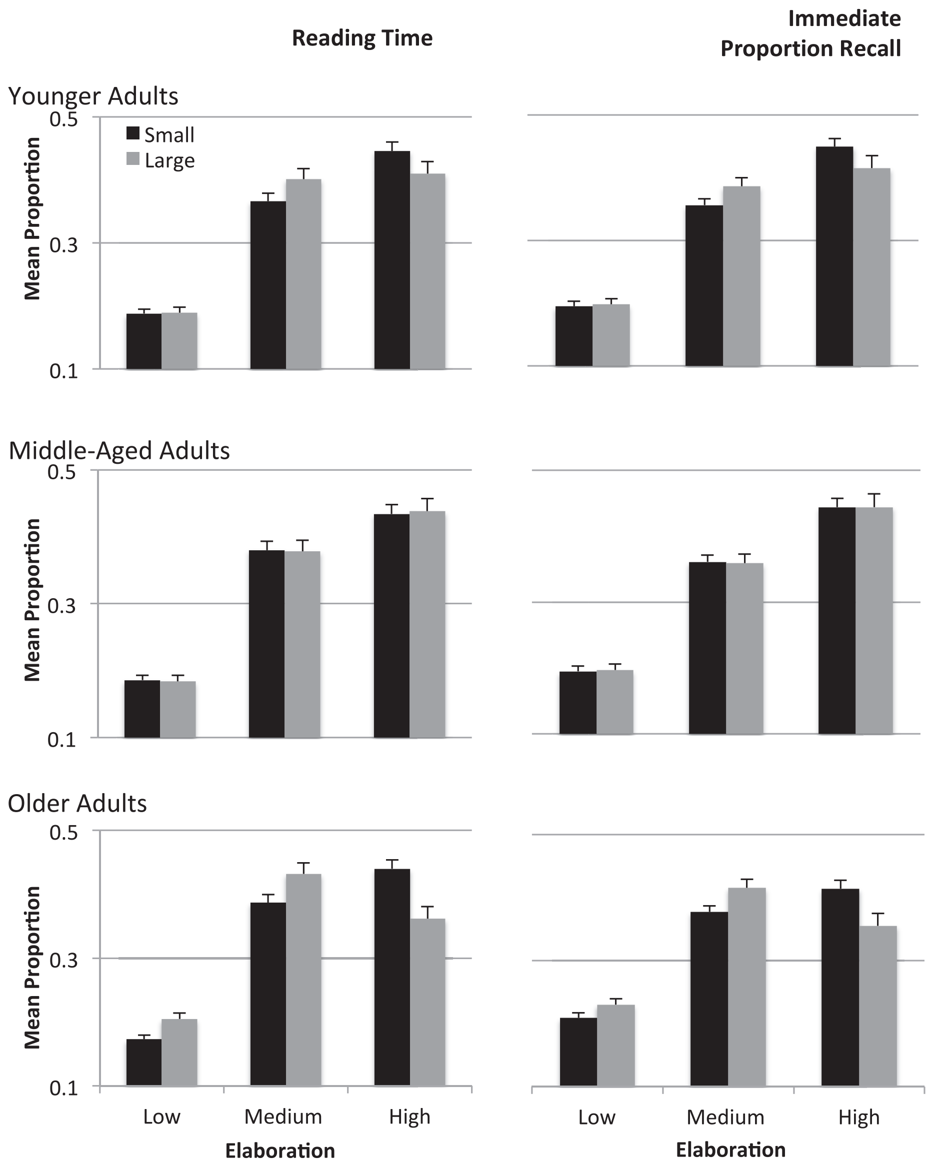

Figure 6. Mean proportion of reading time allocated (left panel) and propositions immediately recalled (right panel) as a function of elaboration level and age in the small and large switch cost conditions. *SR*s are represented by vertical bars.

than the one among younger and middle-aged adults). This was also true for delayed recall, $r_O = .42$, $p = .04$ ($r_Y = .07$, $r_M = .38$, though the differences in correlations for the delayed recall among younger, middle-aged, and older adults did not reach significance). This implied that older adults were more likely to improve their memory performance with the persistence engendered by switch cost.

Discussion

This study used a novel paradigm to examine how readers select and allocate time in an interactive reading environment. We replicated certain effects of aging and in sentence processing, but also extended these findings in a new context. As in earlier literature, we found age similarities in sentence selection and age differences in the processing efficiency of learning new information from text, but we also found that in a reading ecology in which individuals are free to explore and select what they will learn, readers differed in their strategies in adapting to the constraints of the environment as a function of age.

Metcalfe and Jacobs (2010) looked to principles from animal foraging to inspire a new understanding of human learning. We examined the joint influence of information richness and switch cost as adults of different ages read texts in an ecology that afforded control over selection and time allocation. This paradigm allowed us to test two key ideas from foraging theory: (a) that increasing switch cost will lead to longer perseverance in reading texts with consequent improvement in memory, and (b) that readers will prioritize simpler texts for study, especially with increased switch cost. In particular, we were interested in how the applications of these principles would vary with age in adulthood.

Switch Cost Enhances Perseverance in Reading

We found that switch cost had a strong effect on study time allocation, immediate recall, and delayed recall of texts, which supported the hypothesis from the IF model (Pirolli & Card, 1999). A large switch cost was found to be beneficial to learning in terms of increasing perseverance, despite the perceptions that it was less acceptable and more annoying than small switch costs. Prior studies have found that decision makers persisted longer in reading web pages with large switch costs relative to small switch costs (Dennis & Taylor, 2006; Taylor, Dennis, & Cummings, 2013). However, these studies did not assess whether the amount of information gain was also increased by large switch costs. The findings from the current research filled this gap, indicating that learners gained more information when they persisted longer in reading. One practical implication is that contemporary ecologies of reading, where print is at our fingertips, may engender habits of engagement in which readers are prone to invest less effort in particular texts. Our data suggest that such environments may actually diminish learning.

Older adults benefited more from increased switch cost. While the increase in time allocation with switch cost did not vary significantly with age, older adults showed especially good memory performance in delayed recall when switch cost had been large at encoding, and the extra time they allocated was more predictive of immediate recall. Hess (2014) has recently argued that older adults are likely to show decreased intrinsic motivation for cognitive tasks over time because of the differential resource allocation required with age. In our study, participants read naturalistic materials that one might ordinarily encounter if preparing for travel, for example. We speculate that the increase in switch cost enhanced the value of the information that offset these motivational differences. In fact, Castel, Murayama, Friedman, McGillivray, and Link (2013) have demonstrated that when given a list of items with varying value points to learn under a time limit, older adults allocated differentially more time to the high-value items compared with younger adults, and the age difference in recall was eliminated for the high-value items. Therefore, it is possible that older adults selectively focus more on encoding ideas from text in the ecology with a large switch cost because they perceive the information is more valuable compared with an ecology with a small switch cost, which in turn enhances their memory performance.

Information Richness Affects Selection and Reading Efficiency

Readers selected texts that were relatively less information-rich first and then moved progressively to more information-rich texts. More important, this selection strategy did not vary with age. To some extent, these findings contrast with those of Shake et al. (2009), who found that older adults selectively remembered information from more elaborated texts, suggesting a relative preference for information-rich sources. Our texts, however, were in a more moderate range of elaboration than those used by Shake et al. (2009), so that there was less opportunity for readers to take advantage of discourse context, from which older adults might particularly benefit (Stine-Morrow, Miller, Gagne, & Hertzog, 2008). In fact, in terms of propositional content, our complex passages were within a range that has been previously shown to create difficulty for older adults (Stine & Wingfield, 1988). As illustrated by the age by elaboration interaction on effective reading time, older adults showed a significant decrease in the efficiency of encoding ideas as sentence elaboration increased compared to younger and middle-aged adults. Thus, even though the more elaborated sentences contained more information, participants regardless of age selected the items from which information was easier to encode (i.e., sentences that had fewer ideas; Price & Murray, 2012).

Information Foragers Adapt to Switch Cost in Selection and Time Allocation

When the switch cost was increased, foragers distributed their study time so as to allocate relatively more time to the easier texts from which ideas could be more efficiently extracted. In some ways, this effect is similar to the shift-to-easier-materials (STEM) effect in which increased time pressure leads to a shift of time allocation to easier items (Dunlosky & Thiede, 2004; Metcalfe, 2002; Wilkinson, Reader, & Payne, 2012). Although switch cost had some impact on the total time available, we do not believe that our effects were because of perceived time pressure per se. In contrast with studies by Metcalfe (2002) and Wilkinson et al. (2012), for example, who gave participants study time limits before the study sessions to manipulate the time pressure, our participants were generally not aware of how the timing was manipulated. In our study, participants had a uniform time limit across conditions and were not told about the switch cost in advance; rather, they could only discover this property by interacting with the environment. As described earlier, very few participants actually have veridical perceptions of the timing differences that created the switch cost. It may be that although the time delay in the large-switch-cost condition was longer relative to the small-switch-cost condition, the longer delay was still "acceptable" for the learners. In the literature in human-computer interaction, acceptable time delay in loading a web page is defined as time cost that should not trigger web users' dissatisfaction (Dennis & Taylor, 2006). Several studies have attempted to quantify the range of acceptable time delays, and on average, researchers agree that the range is bounded by a short time delay of 2 s or less and a long delay of 8–10 s (Galletta, Henry, McCoy, & Polak, 2004; Nielsen, 1994). The switch costs in our study were well within that limit. Therefore, participants tolerated the increased switch cost by adapting their information search behaviors without conscious awareness.

More important, relative to younger and middle-aged adults, older adults were found to have a greater tendency to allocate time to simpler texts as switch cost increased. As above, we found evidence that older adults were more taxed by the more complex sentences, which may have contributed to the exaggerated tendency to shift away from allocation to these materials with switch cost.

Conclusions

Based on an ecological paradigm of reading, our study provided evidence for preservation with age in the ability to adapt to changing learning environments so as to improve memory performance, with older adults in some ways showing greater adaptation to changes in the ecology. The study of how search mechanisms change across the life span is important not only because technology is creating learning ecologies that require search. Assuming that search is a fundamental mechanism in cognition (e.g., Fu et al., 2015), it also provides a new lens through which to examine how aging impacts the selection of and investment in activities more generally (e.g., Mata & von Helversen, 2015; Stine-Morrow, 2015).

A limitation of this research was that the methodological approach only allowed us to examine adaptation to information ecologies that enhanced relative effectiveness, but we cannot address the extent to which foragers actually achieved optimality. The assessment of optimality within an IF framework entails estimation of information gain functions, as a base of comparison to performance when the opportunity to forage is available. We leave this problem for future research to tackle. Although the paradigm did not allow us to assess the optimality of learning strategies, learners did show adaptations to different switch costs in the learning environment in a way that would approach optimal performance.

Our findings suggest implications to real-life learning situations, providing support for the concern that the availability of multiple resources with fast access may engender relatively superficial learning strategies (Carr, 2010). We certainly do not intend a philistine position that such information ecologies are to be avoided, and of course, we are not recommending that information technology should include loading delays to improve learning. As a matter of fact, prolonged delays may even cause dissatisfaction and demotivate learners. However, given that contemporary ecologies of reading increasingly afford fast switching among sources that may put learners at risk for underallocation of effort, the designer of learning technology may want to incorporate features to counteract shallow processing, for example by including comprehension probes. In addition, it might be useful to provide scent cues that indicate the relative "values" of the sources for particular goals to engender top-down control, so that learners can allocate their time effectively. Future research can also investigate how types of scent cues other than text elaboration interact with switch cost to impact learning. Given that the effects of switch cost tended to increase with age, such considerations make be especially important in the design of learning technologies for older adults.

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