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Aging Selectively Impairs Recollection in Recognition Memory for Pictures: Evidence From Modeling and Receiver Operating Characteristic Curves

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Young and older adults were tested on recognition memory for pictures. The Yonelinas high threshold (YHT) model, a formal implementation of 2-process theory, fit the response distribution data of both young and older adults significantly better than a normal unequal variance signal-detection model. Consistent with this finding, nonlinear *z*-transformed receiver operating characteristic curves were obtained for both groups. Estimates of recollection from the YHT model were significantly higher for young than for older adults. This deficit was not a consequence of a general decline in memory; older adults showed comparable overall accuracy and in fact a nonsignificant increase in their familiarity scores. Implications of these results for theories of recognition memory and the mnemonic deficit associated with aging are discussed.

Keywords: aging and episodic memory, item recognition, two-process theory, ROC curves, Yonelinas high threshold model

Recognition memory tests the abilities that enable an individual to identify an old friend in a sea of faces or to know that he or she has in fact heard that joke before. In laboratory studies of recognition memory, participants are presented with a list of to-be-remembered items. During a test phase, the participant is presented with a series of probe items, some of which were present in the list and some of which are new items. The participant's task is to determine which are which.

Numerous theorists have argued that recognition memory is not a unitary ability but rather is composed of two processes (Atkinson & Juola, 1974; Mandler, 1980; Tulving, 1983; Yonelinas, 1997). In the modal version of this idea, one component, referred to as recollection, describes people's ability to recover vivid detailed information about the study episode. Recollection provides strong evidence of prior occurrence that enables people to endorse recollected old probe items with certainty. In addition, two-process theory postulates that familiarity, a memory process that corresponds to enhanced perceptual or semantic fluency for recently experienced items, also supports recognition performance even in the absence of vivid recollection. Researchers have developed a variety of experimental techniques designed to measure recollection and familiarity, including the process dissociation procedure (Jacoby, 1991), the remember–know procedure (Tulving, 1985), tests of source memory (Dywan & Jacoby, 1990), and the analysis of receiver operating characteristic (ROC) curves (Yonelinas, 1994, 1997). Numerous experimental dissociations between recollection and familiarity have been observed. For instance, recollective detail becomes available later than familiarity in retrieval (Hintzman & Curran, 1994) and depends on the integrity of the hippocampus (Fortin, Wright, & Eichenbaum, 2004; Yonelinas et al., 2002).

Aging and Two-Process Theory

Changes in memory function with normal aging have been studied from the perspective of two-process theory by using a variety of techniques. The consensus from these studies is that aging affects recollection. Insofar as recollection is similar to recall and age deficits in recall have been extensively observed (e.g., Kahana, Howard, Zaromb, & Wingfield, 2002; Naveh-Benjamin, 2000; Onyper, Hoyer, & Cerella, in press), this is not surprising. There is less consensus as to whether the deficit with aging is specific to recollection or whether aging also results in a decrease in familiarity as well (Hoyer & Verhaeghen, 2006; Prull, Dawes, Martin, Rosenberg, & Light, 2006).

In associative recognition, participants study pairs of items (e.g., A–B, C–D) and must distinguish old pairs from re-paired lures (e.g., A–D). Because each of the components of a re-paired lure should be familiar, associative recognition is believed to rely preferentially on recollection. Some have argued that aging impairs associative recognition more than item recognition, which presumably depends on both recollection and familiarity (Light, Patterson, Chung, & Healy, 2004; Naveh-Benjamin, 2000; Naveh-Benjamin, Guez, Kilb, & Reedy, 2004; Naveh-Benjamin, Hussain, Guez, & Bar-On, 2003). In particular, Light et al. (2004) showed that associative recognition performance for older adults was comparable to that observed for young adults given only a short amount of time to respond. Given the finding that recollective information is retrieved more slowly than information about fa-

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miliarity (Hintzman & Curran, 1994; see also Rotello & Heit, 1999), this is especially suggestive of a strong recollective deficit in older adults.

Toth and Parks (in press) estimated recollection and familiarity for young and older adults by using the remember–know procedure for memory of words presented in various voices and fonts. On the basis of their findings, they argued that normal aging was associated with reductions in both recollection and familiarity. In contrast, other remember–know studies (e.g., Bastin & Van Der Linden, 2003) have argued that the mnemonic deficit associated with aging is specific to recollection, with familiarity slightly higher for older adults. The potential lack of independence of recollection and familiarity makes it particularly difficult to estimate recollection and familiarity from remember–know judgments, even if one takes the remember–know procedure at face value in directly measuring categorically different responses (an assumption that may not be viable; see Wixted & Stretch, 2004). Another criticism of the remember–know procedure is that remember and know judgments are not process pure insofar as sufficiently strong familiarity for an item may lead to a remember judgment.

Other methods for assessing recollection and familiarity have been used to assess the mnemonic deficit in normal aging. Reasoning that recall depends on recollection but recognition relies on both recollection and familiarity, Quamme, Yonelinas, Widaman, Kroll, and Sauvé (2004) estimated recollection and familiarity from structural equation modeling of recall and recognition scores for adults that varied in age and hypoxic damage. The results of the structural equation modeling argued that age affected recollection but not familiarity. Similarly, Jennings and Jacoby (1997) suggested on the basis of process dissociation procedure data that older adults were impaired at recollection while relatively unaffected in their automatic memory processes, that is, familiarity.

Modeling and ROC Curves as a Constraint on Theory

Although there are many ways to assess recollection and familiarity (for a review, see Yonelinas, 2002), in this article we will focus on fitting models of item recognition to ROC curves. Measures of recognition memory describe discriminability as a joint function of both the hit rate, the probability of endorsing an old probe item as old, and the false-alarm rate, the probability of incorrectly endorsing a new probe item as old. Neither the hit rate nor the false-alarm rate by themselves place meaningful constraints on models of recognition memory. For instance, a high hit rate coupled with a high false-alarm rate does not indicate good memory but rather a subject with a very liberal response bias. Only the relationship between the hit rate and false-alarm rate contains information about discriminability. A single measurement of both hit rate and false-alarm rate provides a single point in ROC space.

ROC curves, constructed from observing memory at several different levels of confidence, combine several hit rate and false-alarm rate pairs to trace out a curve in ROC space. Suppose we have an experiment in which the participant rates each recognition probe on a scale from 1 to 6, with 6 corresponding to the highest rating of confidence that the probe item was presented on the list. We can calculate a meaningful hit rate and false-alarm rate for each of five criteria. For instance, we might calculate the hit rate by counting only "6" responses as endorsing the item as old. Alternatively, we could calculate hit rate by counting both "5" and "6" responses as endorsing the probe item as old. By calculating hit rate and false-alarm rate for each possible criterion, we obtain a trajectory through ROC space. Because ROC curves measure discriminability simultaneously at several response criteria, they place a strong constraint on models of recognition performance.

Yonelinas High Threshold Model (YHT)

The Yonelinas high threshold model (YHT; Yonelinas, 1994, 2002) proposes that old test probes are recollected with probability R. If an old item is not recollected, the recognition decision relies on a familiarity process. Familiarity in the YHT is modeled as an equal variance signal-detection process. The strength of old probe items is drawn from a normal distribution. The strength of new probe items is drawn from a normal distribution with the same standard deviation as the old-item distribution. The mean of the old-item distribution is assumed to be different from that of the new-item distribution, a difference that is measured by a parameter, d'_{YHT}, which measures the distance between the old- and new-item familiarity distributions in units of their common standard deviation. Although they are not necessarily strong assumptions of the model, in previously published work the probability of recollecting new items has been assumed to be zero and the standard deviations of old and new item familiarity distributions have been assumed to be equal.

The two components of the YHT give rise to distinctive patterns of responses in the ROC curve. Imagine for a moment that familiarity is absent from the recognition decision ($d'_{\mathrm{YHT}} = 0$) and that the subject is relying solely on recollection. At the most conservative response criterion, the hit rate is R and the false-alarm rate is zero. At the most liberal response criterion, the hit rate and false-alarm rate are both one. As the response bias changes between conservative and liberal, the false-alarm rate increases from zero on the basis of guessing. Because there is no discriminability between old and new items on the basis of familiarity, the change in the hit rate associated with guessing is $1 - R$ times the change in the false-alarm rate, resulting in a straight line. The YHT generates very different ROC curves if recollection is set to zero and d'_{YHT} is nonzero. Under these circumstances, a smooth ROC curve that is symmetric around the cross-diagonal results. Combining these two components, the result is a curved, asymmetric ROC curve that terminates on the hit-rate axis.

Two Processes or One Variable Process?

In contrast to the view that two processes, recollection and familiarity, support recognition performance, a widespread view that is especially broadly held in the mathematical modeling community is that recognition performance is supported by a single but variable process. One possibility is that the difference between old and new distributions is not limited to a change in the mean, as in the equal variance signal-detection model, but is also associated with a change in the variability of the two distributions. This model is referred to as the normal unequal variance (NUV) signal-detection model. The NUV would obtain, for instance, if the increment in strength each item acquired as a consequence of study was distributed normally. The NUV can be parameterized by d'_{NUV}, the difference between the means of the distributions, in units of the standard deviation of the new-item distribution, and σ_{O}, the standard deviations of the old-item distribution, in units of the standard deviation of the new-item distribution. Unlike the equal variance signal-detection model, the NUV is able to generate asymmetric ROC curves consistent with those observed in typical recognition memory experiments. Although the YHT and NUV generate ROC curves that look similar to the naked eye, they make qualitatively different predictions about the form of the ROC curve when it is z transformed.

In addition to the constraints provided by ROC curves, the z-transformed ROC (z-ROC) curve allows additional insight into the processes giving rise to recognition discriminability. If the recognition decision is the result of the NUV, then the z-ROC curve will appear linear, with the intercept of the z-ROC curve given by d'_{NUV} and the slope of the line given by σ_{O}. In contrast, the YHT predicts curvilinear z-ROC curves, with the curve inflected upward on the left-hand side corresponding to the most conservative response criteria to the extent that R is greater than zero. It should be noted that the YHT can predict linear z-ROC curves with a slope of 1 if $R = 0$. On this count, the bulk of the evidence lends support to the NUV; linear, or nearly linear, z-ROC curves with a slope significantly less than 1 are typically observed in item recognition (e.g., Glanzer, Kim, Hilford, & Adams, 1999; Heathcote, 2003; Hirshman & Hostetter, 2000; Ratcliff, McKoon, & Tindall, 1994; Ratcliff, Sheu, & Gronlund, 1992; Van Zandt, 2000), although not all studies report this finding (Yonelinas, Dobbins, Szymanski, Dhaliwal, & King, 1996). The widespread belief that z-ROC curves are linear for item recognition has led to models of item recognition that are designed specifically to generate linear z-ROC curves (e.g., Chappell & Humphreys, 1994; McClelland & Chappell, 1998; Shiffrin & Steyvers, 1997). Although the YHT and NUV are good models to compare with each other—they have the same number of parameters yet embody very different assumptions about the processes underlying item recognition—they are not the only possible models of recognition performance. For instance, to explain data from participants administered the anticholinergic scopolamine, Sherman, Atri, Hasselmo, Stern, and Howard (2003) proposed a variable recollection model, in which recollection is not an all-or-none process but can give rise to different gradations of confidence. Similar ideas have been proposed in dealing with data from associative recognition (Kelley & Wixted, 2001; Macho, 2004). In addition to the additional layer of complexity that can arise from considering more elaborate recollection, it is also possible to generate discrete-state models that abandon the concept of strength as a primitive concept entirely, yet produce a wide variety of ROC curves (Malmberg, 2002).

Previous Work Modeling Aging by Using ROC Curves

Given the theoretical constraints offered by ROC curves and the desirability of quantitative modeling of task performance in estimating the strength of cognitive processes, it is perhaps surprising that relatively little work has been done in fitting ROC curves to data from young and older adults. Healy, Light, and Chung (2005) examined performance in an associative recognition task. Pairs of words were presented at study. At test, completely new pairs (e.g., Study A–B, C–D, Test E–F) as well as pairs composed of mismatched study terms (e.g., Study A–B, C–D, Test A–D) were presented during a recognition test. Participants were instructed to reject both the new and the re-paired lures. In addition to finding an age-related deficit in recognition, Healy et al. (2005) also found impaired item recognition for older adults comparing hit rate from intact pairs with false-alarm rates from new pairs. They modeled item (intact vs. new) and associative (intact vs. rearranged) ROC curves by using a variety of two-process models. Healy et al. (2005) found that the models of associative recognition converged in predicting that older adults had impaired recollection relative to young adults. In contrast, however, the models of associative recognition produced divergent conclusions as to whether there is an age effect on familiarity. Complicating matters, however, the model fits to the data from item recognition of pairs resulted in the opposite conclusion, that aging is associated with a decrement in familiarity but did not have a significant effect on recollection.

Toth and Parks (in press) examined ROC curves for young and older adults performing item recognition for words presented auditorily in either the right or left ear in either a male or female voice. In the hard condition, participants were instructed to answer "recollect" in response to a test probe if they remembered in which ear the word was presented. In the vague condition, participants were instructed to answer "recollect" if they remembered any of the details of the probe item's presentation. If the probe was not recollected, Parks et al. collected a confidence rating on a 6-point scale. By collapsing the recollect responses with the highest-confidence yes responses, Parks et al. were able to generate ROC curves for young and older adults. In fitting the YHT model to these ROC curves, Parks et al. found that both R and d'_{YHT} were lower for older adults than for young adults, suggesting that both recollection and familiarity were affected by age. A potential limitation of this approach is that the YHT may not have provided a better fit to the experimental data than the NUV model, rendering the interpretation of the parameter estimates ambiguous. This concern is further exacerbated by the finding of linear z-ROC curves, a qualitative prediction of the NUV that is inconsistent with the YHT with nonzero recollection.

The present study differs from these previous efforts in a number of dimensions. We studied simple item recognition of travel pictures. This procedure should eliminate any potentially complicating factors associated with examining item recognition of pairs within the context of associative recognition[1] (Healy et al., 2005) or the effect of criterial recollection instructions (Toth & Parks, in press). The use of travel pictures as to-be-remembered stimuli is a methodological difference compared with the bulk of previous recognition studies that have traditionally studied recognition for words. Previous studies have suggested robust recollection of travel pictures (Schwartz, Howard, Jing, & Kahana, 2005; Sherman et al., 2003). Finally, insofar as the YHT is quite controversial within the verbal learning community (Heathcote, 2003), we will fit both the YHT and the NUV to the data and evaluate the resulting fits before interpreting age differences in the parameters.

[1] For instance, it is possible that when studying pairs, participants search for relationships among the words. Strategic encoding and subsequent retrieval of this associative information could be used to reject new as well as rearranged lures. Any age differences in recollection observed in item recognition embedded in an associative paradigm could conceivably be attributable to older adults differentially adopting this strategy. Insofar as the item recognition paradigm places less emphasis on associative information, an item recognition experiment might be less susceptible to this type of criticism.

Experiment

To assess age differences in recollection and familiarity, we undertook a multiple-criteria item-recognition experiment with young and older adults. We examined both ROC curves and z-ROC curves to characterize the discriminability of young and older adults at different response criteria. Subsequently, we fit the YHT and NUV to the response distributions of each subject to evaluate the models as well as estimate recollection and familiarity across age groups.

Method

Participants

A total of 43 young adults and 33 older adults participated. Young adults were recruited from the Syracuse University community over the summer and consisted of a combination of undergraduates and graduate students. Older adults were recruited through the registry of the Adult Cognition Laboratory at Syracuse University. The mean age for the young adult group was 24.4 years (SD = 2.7 years), and the mean age for the older group was 71.2 years (SD = 4.2 years). Women comprised 19 of 43 of the young participants and 20 of 33 of the older participants. Mean years of education were 18.3 (SD = 2.6 years) for the young adults and 15.9 (SD = 3.0 years) for the older adults. Older adults performed a battery of standard cognitive tests (forward and backward digit span, identical pictures task, symbol digit task) on their first visit to the lab. Thirty-one of the older participants had previously served as participants in another cognitive experiment in the Adult Cognition Laboratory, typically a skill-learning experiment. Young adults did not perform a battery of cognitive tests and were not previously participants in cognitive experiments conducted in our laboratories.

Procedure

Participants were given a picture recognition task in two sessions conducted at roughly the same time of day on 2 consecutive days. On each session, participants studied three lists of 128 digital pixmaps with resolution of 350 × 232 pixels. The images subtended roughly 5° of visual angle. Images were obtained from planetware.com, a travel picture Web site. The picture pool we used (Schwartz et al., 2005) included a variety of scenes, outdoor and indoor, from travel destinations throughout the world, including nature pictures as well as urban scenes. The pool was constructed such that all pictures that contained text or that contained images that would be obviously emotionally salient to a large proportion of viewers (e.g., images of the World Trade Center in New York City) were eliminated from the pool. During study of the list, images were presented on the screen for 1 s, with a screen blank for 0.5 s between pictures. After each presentation of a list, participants were given 256 probes, half of which were in the list and half of which were new pictures. The test lists were constructed by using an algorithm that attempted to equalize the distribution of relative lags, the difference in presentation of serial position between adjacent old test items, such that relative lags with an absolute value of 1 to 5 were presented approximately equally often. This algorithm first assigned the old or new status of each test item randomly and then attempted to insert relative lag pairs into pairs of successive old tests subject to the constraint that no pictures were tested more than once. This algorithm was the same as that used in Schwartz et al. (2005). The results of the relative lag analyses will not be discussed in this article.

In response to each test picture, participants pressed a key from 1 to 6 to describe their confidence that the item was presented during study, with a 6 corresponding to an absolutely certain "old" response and 1 corresponding to an absolutely "new" response. These responses were collected by using a computer keyboard with the keys *1*, *2*, and *3* replacing *z*, *x*, and *c*, respectively, and the keys *4*, *5*, and *6* replacing the comma, period, and slash keys, respectively (standard qwerty layout). This allowed participants to respond comfortably by using only the first three fingers of each hand. Participants were instructed to use all six keys and to respond as quickly as possible without sacrificing accuracy. So that participants became familiarized with these procedures, they studied and were tested on a practice list prior to receiving the first study list. After the practice session, participants were provided with feedback about their mean reaction time and the distribution of their responses. Participants were not given explicit instructions as to what strategy they should use to encode the pictures but were simply instructed to try to remember the pictures for a subsequent memory test.

The second experimental session was conducted on the day immediately after Session 1. The two sessions were identical in procedure except that the participants completed a consent form and demographic measures at the beginning of Session 1. Over the two sessions, each subject responded to a total of 768 old-item test probes and 768 new-item test probes.

Modeling

To assess the degree to which recollection and familiarity contributed to recognition performance for young and older adults, we fit the YHT model (Yonelinas, 1994, 1997, 2001) to each participant's response distribution. To do this, we did a comprehensive search of R and d'_{YHT}. For each value of R and d'_{YHT}, we constructed a model-derived ROC curve. We then slid the response criteria along the ROC curve incrementally to find the lowest possible chi-square between the observed response distribution and the model's predictions. As far as we are aware, this precise technique has not been used previously. The data contain 10 degrees of freedom corresponding to the six responses to old items and the six responses to new items. The model includes the two free parameters R and d'_{YHT} as well as the five response criteria. The fit, therefore, has 3 degrees of freedom for each subject.

Because the YHT has been criticized as a description of item recognition, we used the same procedure to fit the NUV to each participant's data. The procedure was identical except that the ROC curves were generated by the NUV with parameters σ_{O} and d'_{NUV}. We were able to compare the fits from the YHT with the fits obtained from the NUV as well as provide an alternative way to assess the effects of aging on model parameters.

Results

We examined the performance of young and older adults by using a variety of methods. First, we examine hit rate, false-alarm rate and d'. Next, we examine ROC and z-ROC curves. Then we describe the results of modeling the detailed pattern of performance across response criteria by using the YHT and NUV.

Hit Rates and False-Alarm Rates

We evaluated hit rate and false-alarm rate for each of the possible criteria. We labeled the criterion according to the lowest response that would count as an endorsement of the item as old for the purposes of calculating hit rate. For instance, a response of "4" would be counted as a *yes* response for Criteria 1–4 but not for Criterion 5 or Criterion 6. The hit rates for young and older adults, along with t statistics for the comparisons, are shown in *Table 1*. There were no significant differences between hit rate for young and older adults at any of the response criteria.

The results for the false-alarm rate calculations are shown in Table 1. At the most stringent response criteria, older adults showed a significantly higher false-alarm rate than young adults. The comparison at Criterion 5 also remained significant when evaluated with a Wilcoxon signed-ranks test (W = 912, $p < .05$). From this we conclude that there is a tendency for older adults to

Table 1
Mean Hit Rate, False-Alarm Rate, and d′ for Younger and Older Adults for Each of the Possible Criterion Values

Criterion	Young	Older	$t(74)$
	Hit rate		
6	0.42 (.03)	0.46 (.03)	−0.80
5	0.54 (.02)	0.59 (.03)	−1.25
4	0.64 (.02)	0.67 (.03)	−0.80
3	0.73 (.02)	0.74 (.03)	−0.23
2	0.85 (.02)	0.85 (.03)	0.10
	False-alarm rate		
6	0.08 (.01)	0.13 (.02)	−2.10*
5	0.17 (.01)	0.23 (.02)	−2.46*
4	0.29 (.02)	0.31 (.02)	−1.01
3	0.42 (.03)	0.43 (.03)	−0.15
2	0.61 (.04)	0.62 (.04)	−0.04
	d'		
6	1.40 (.08)	1.21 (.08)	1.71
5	1.14 (.07)	1.04 (.06)	1.02
4	0.98 (.07)	0.99 (.06)	−0.14
3	0.89 (.07)	0.92 (.07)	−0.31
2	0.84 (.07)	0.87 (.06)	−0.36

Note. A criterion of 4 indicates that responses of “4” or greater are counted as *yes* responses for the purposes of this analysis. Standard errors are given in parentheses.
* $p < .05$.

have higher false-alarm rates than young adults, but this tendency is observed only at the most stringent criteria.

Accuracy

Of course, it is impossible to learn anything about recognition discriminability by examining hit rate or false-alarm rate in isolation. Figure 1 shows averaged untransformed ROC curves for young and older adults. This just plots the hit rate as a function of false-alarm rate; both hit rate and false-alarm rate can be found in Table 1. In reading this figure, recognition discriminability is read off informally by noting the distance of a point from the diagonal. The first thing that can be noted from the figure is that it appears that older adults use a less wide range of response biases, which can be seen from the fact that the older adults’ ROC curve, while having a similar overall level of discriminability to that of young adults, is less widely spread. Although discriminability for the groups is very similar, there are slight differences. The ROC curves for young and older adults cross over, with slightly better discriminability for young adults at more conservative response criteria (to the left of the figure) but slightly better discriminability for older adults at more liberal response criteria (to the right of the figure). It would obviously be desirable to evaluate this impression about the crossover of age on discriminability with response criterion in a completely unbiased and theory-neutral way. Unfortunately, all possible measures of discriminability are based on some model. The most widely used model of recognition discriminability is to calculate d' under the standard signal-detection assumptions as z(hit rate) − z(false-alarm rate). This is equivalent to either the YHT with $R = 0$ or the NUV with $\sigma_O = 1$. Although this model of discriminability is certainly incorrect for these data (as can be seen clearly from the asymmetry of the observed ROC curves in Figure 1), d' is a widely used measure of recognition discriminability. Table 1 shows d' for young and older adults for each of the response criteria. At conservative criteria, young adults show a tendency toward greater discriminability. This tendency diminished and even reversed, such that at more liberal response criteria, older adults actually showed slightly higher discriminability than young adults. Although none of the pairwise comparisons at the various response criteria showed a significant difference, the change in age differences appeared systematic with response criteria. To test for this, we conducted a repeated measures analysis of variance on d' with age and criterion as factors. We found significant effects of response criterion, $F(4, 296) = 116.4$, $MSE = 2.62$, $p < .001$, as well as a significant interaction of age and response criterion, $F(4, 296) = 8.34$, $MSE = 0.19$, $p < .001$.

Although there were apparently no gross age differences in overall recognition performance, there was a change in the effect of age across response criteria. The foregoing analyses indicate that what age differences there are are manifest in relatively subtle properties of the shape of the ROC curves. We undertook subsequent analyses, including formal modeling, to reveal these differences.

Nonlinearity of z-ROC Curves

The YHT and NUV make qualitatively different predictions regarding the shape of the ROC curve when it is z-transformed, the z-ROC curve. We examined z-ROC curves for young and older adults. The results of a regression analysis showed that both young and older adults had a significant quadratic trend. For young adults, the best-fitting intercept was $0.83 \pm .06$ ($M \pm SE$), $t(42) =$

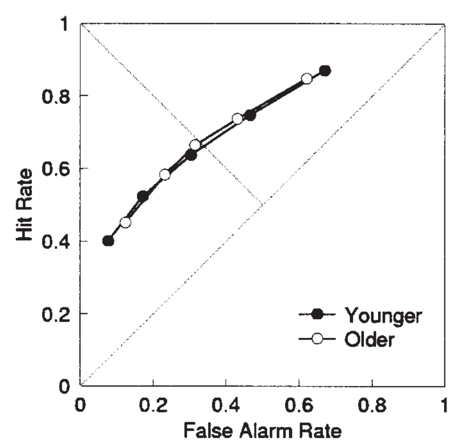

Figure 1. Young and older adults show comparable overall recognition accuracy. Receiver operating characteristic (ROC) curves show hit rate as a function of false-alarm rate for each of the five criteria that are possible with responses on a 6-point scale. If there were no discrimination between old and new test probes, these curves would land on the diagonal running from the lower left to upper right corners. The extent to which the curves are above the diagonal reflects participants’ ability to discriminate old from new items. ROC curves for young and older adults overlap, suggesting comparable levels of overall recognition performance. Both curves show noticeable asymmetry with respect to the cross-diagonal. This rules out an equal variance signal-detection process.

13.4, $p < .001$; the linear coefficient was $0.832 \pm .009$, $t(170) = 89.3$, $p < .001$; and the quadratic coefficient was $0.102 \pm .006$, $t(170) = 18.0$, $p < .001$. For older adults, the best-fitting intercept was $0.86 \pm .06$, $t(33) = 14.4$, $p < .001$; the linear coefficient was $0.87 \pm .01$, $t(134) = 68.6$, $p < .001$; and the quadratic coefficient was $0.084 \pm .009$, $t(134) = 9.1$, $p < .001$. The significant quadratic terms are inconsistent with the NUV, which predicts a linear z-ROC, but are consistent with the YHT (see Figure 2).

Model Fitting

To properly compare differences in the recognition performance of young and older adults, it is necessary to first have a model that properly describes the shape of the ROC curve. Accordingly, we fit the YHT and the NUV to the ROC curves of each subject in the experiment. The YHT fit the young adult data better than did the NUV. The mean chi-square for young adults was 5.60 for YHT. The mean chi-square for the NUV was 11.52, which was significantly higher, $t(42) = 4.30$, $p < .001$. The fit of the YHT to older adults' data was also somewhat better than that of the NUV. The average chi-square for the fit of the YHT to older adults was 5.58, whereas the average chi-square for the fit of the NUV was 7.90, $t(32) = 2.37$, $p < .03$.

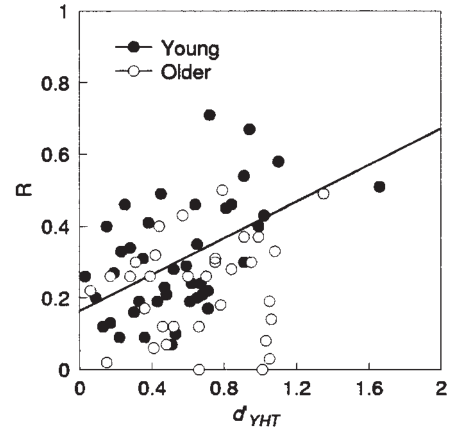

Figure 3. Distribution of Yonelinas high threshold (YHT) model parameters from young and older subjects. For each subject for whom YHT model parameters were available, R and d'_{YHT} are plotted as a function of each other. As a group, young participants had a significantly higher average estimated R, but the older adults had a nonsignificantly higher average d'_{YHT}. It is interesting that R and d'_{YHT} were significantly correlated with each other for young but not older participants. The straight line is the result of a linear regression to the data from young adults.

Model Parameters

Armed with a model that describes the shape of the ROC curves, we can now ask about age differences in the model parameters. We examined model estimates of recollection and familiarity for young and older adults. For the YHT, we found that the mean R for young adults ($.30 \pm .02$) was significantly greater than the mean R for older adults ($.23 \pm .02$), $t(72.9) = 2.22$, $p < .03$. In contrast, d'_{YHT} was not greater for young adults. Rather, there was a trend for the mean d'_{YHT} to be greater for older adults ($.67 \pm .06$) than for young adults ($.55 \pm .05$), although this effect did not reach significance, $t(69.4) = 1.41$, $p < .15$. Figure 3 shows the best-fitting parameters from the YHT for each participant in this study.

Although the NUV model did not fit the data as well as the YHT model did, we nonetheless compared model parameters from the NUV across age groups. These provided convergent results for the conclusions we reached from the YHT. The variance of the old item distribution, σ_{O}, was greater for young adults ($1.46 \pm .04$) than for older adults ($1.31 \pm .05$), $t(64.9) = 2.50$, $p < .02$. In contrast, d'_{NUV} did not show an age effect. For young adults, the mean d'_{NUV} was $1.2 \pm .1$, whereas for older adults it was $1.09 \pm .08$. This difference was not significant, $t(73.5) = 0.92$. As for the YHT, the parameter of the NUV associated with skewed ROC curves, σ_{O}, showed an age effect, whereas the parameter of the NUV corresponding to a univariate signal-detection process, d'_{NUV}, did not show an age effect.

Given the fact that the YHT and NUV can produce identical ROC curves if $R = 0$ and $\sigma_{\mathrm{O}} = 1$, it is natural to ask whether the

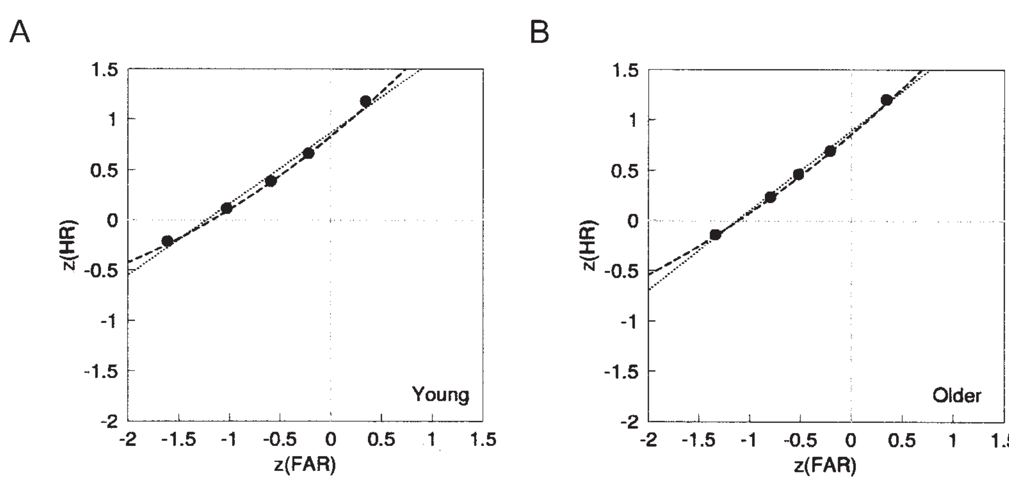

Figure 2. The z-transformed receiver operating characteristic curves for (A) young and (B) older adults. The results of linear (dotted) and quadratic (dashed) regressions are shown for each group. For each group, the quadratic coefficient was significant. HR = hit rate; FAR = false-alarm rate.

parameter estimates across models are correlated with each other. Collapsing across both subject groups, we observed significant correlations for both R and σ_O (Pearson's $r = .67$), $t(74) = 7.69$, $p < .001$, and for d'_{YHT} and d'_{NUV} (Pearson's $r = .74$), $t(74) = 9.36$, $p < .001$. These correlations are a consequence of the strong correspondence between the model parameters.

Visual inspection of the best-fitting values of R and d'_{YHT} (see Figure 3) suggested that model estimates of recollection and familiarity were not independent of each other across subjects. To assess this, we generated correlation coefficients between R and d'_{YHT} for young and older adults. It is interesting that model estimates of R and d'_{YHT} were significantly correlated across participants for young participants ($r = .51$, $p < .001$) but not for older participants ($r = .15$, $p > .4$). A similar pattern of results was found for the parameter estimates from the NUV in which σ_O and d'_{NUV} were significantly correlated across subjects for young participants ($r = .58$, $p < .001$) but not for older participants ($r = .22$, $p > .2$).

Figure 3 includes a regression line for young adults. It appears that a cluster of older participants with high d'_{YHT} but very low R is responsible for the difference in the observed correlations in parameters across age groups.

Discussion

We examined recognition memory of travel pictures in young and older adults. For these groups of participants, there was no gross effect of age on overall recognition performance. Thus, any age differences would be attributable to relatively subtle changes in the pattern of responses across multiple criteria. The z-ROC curves for young and older adults had significant quadratic curvature, suggesting that recognition memory was not well described by the NUV signal-detection model. Consistent with the finding of nonlinear z-ROC curves, modeling results showed that the NUV model did not fit the response distributions for either young or older adults as well as did the YHT model, which assumes a discrete recollective process in addition to a familiarity-based signal-detection process. Despite the lack of a gross deficit in overall accuracy, older adults showed significantly lower levels of recollection than did young adults. This finding confirms a number of other studies that argued that recollection, estimated in various ways in various experimental settings, is preferentially impaired in older adults (Bastin & Van Der Linden, 2003; Jennings & Jacoby, 1997; Quamme et al., 2004). In contrast, we found no evidence for an age deficit in familiarity. This is not consistent with other studies that have found that aging is associated with decreased familiarity (Prull et al., 2006; Toth & Parks, in press).

One discrepancy between the current study and the vast majority of previous work on the effects of aging on item recognition is the fact that we did not observe drastic effects of age on overall recognition performance. Although we observed some evidence for higher false-alarm rates for older adults at the most stringent criteria (see Table 1), the age differences we observed in modeling the data are best described as reflecting a relatively subtle change in the shape of ROC curves in older adults. There are several factors that might account for this. One possibility is that our use of travel pictures allowed older adults to make effective use of more extensive travel experience or perhaps more extensive geographical and cultural semantic knowledge in encoding the stimuli. Another possibility is that our older subject sample, the vast majority of whom had participated in previous cognitive experiments, was particularly motivated, or perhaps their prior experience with cognitive testing provided some very general practice effect. Further experimentation would clearly be necessary to distinguish these various possibilities. It is notable, however, that despite the lack of a dramatic effect of age on discriminability, there was nonetheless a reliable decrement in the proportion of recollective responses for older adults.

Recognition memory poses a number of challenges to the researcher interested in characterizing the performance of different groups. In the present study, we were able to measure hit rate and false-alarm rate for each of five criteria. Had we collected only yes–no responses, we might have found either no deficit associated with aging, if the experiment worked out to have a liberal response criterion, or a deficit restricted to an increased false-alarm rate for older adults, if the experiment worked out to implement a conservative response criterion. By observing performance at multiple response criteria, we were able to obtain a more complete picture of subjects' recognition memory.

Moreover, there are considerable advantages to using cognitive models to describe the data. Traditional calculations of d' to characterize discriminability is essentially fitting a model to the data, in this case the equal variance signal-detection model, a model that fails to describe observed skewed ROC curves. We were able to demonstrate that the YHT provides a fit superior to those of the equal variance signal-detection and NUV models to the ROC curves of both young and older subjects. The data in this experiment were composed of 10 dependent variables. The use of the YHT enabled us to boil the pattern of responses across these 10 dependent variables into a psychologically rich interpretation. Of course, this interpretation depends on the validity of the YHT, but this statement applies equally well to all models of recognition discriminability.

It is interesting that whereas estimates of recollection and familiarity were correlated across subjects for young adults, no such relationship was observed for older adults. In the YHT, stochastic independence is typically assumed to hold between recollection and familiarity at retrieval. This greatly simplifies the equations that the model implements. The assumption of independence is also used in other experimental applications of two-process theory, including the process dissociation procedure and corrected estimates of knowing in the remember–know procedure. Although the finding of correlated estimates of recollection and familiarity in the present study does not bear on the question of stochastic independence at retrieval, it is worth pointing out that some recent criticisms of dual-process theory (Dunn, 2004) are actually criticisms of the independence assumptions. Furthermore, most authors argue not only that both recollection and familiarity depend on medial temporal lobe structures, but that the hippocampus supports recollection whereas surrounding regions of medial temporal lobe cortex support familiarity (e.g., Davachi, Mitchell, & Wagner, 2003; Fortin et al., 2004; Ranganath et al., 2004; Yonelinas et al., 2002). The hippocampus receives input from cortical regions of the medial temporal lobe, so it is not hard to imagine that a strong form of stochastic independence between the processes would not hold. The reasons why aging might be associated with a weakening of the functional connection between recollection and familiarity are quite opaque at this time.

The YHT Model and the Signal-Detection Framework

This is the first study that we are aware of in which the YHT and NUV models were directly compared with each other and the YHT was shown to generate a superior fit to the data. This was found separately for both young and old participants. Moreover, a qualitative prediction of the YHT—curvilinear z-ROC curves—was observed, in contradiction to a qualitative prediction of the NUV. Although we are aware of other studies that have reported U-shaped z-ROC curves (Sherman et al., 2003; Yonelinas et al., 1996), neither of them has had nearly so much data per participant, nor so many participants on which to report. Under at least some circumstances, the YHT provides an excellent account of the distribution of participants' responses as well as the qualitative shape of z-ROC curves.

Given the widespread reports of linear (or nearly linear) z-ROC curves (Heathcote, 2003; Hirshman & Hostetter, 2000; Ratcliff et al., 1992, 1994; Van Zandt, 2000), what could account for the difference between the present results and earlier work showing that the NUV provides a better fit to ROC data (e.g., Heathcote, 2003)? One difference between the current study and previous work that showed linear z-ROC curves is the use of travel pictures as to-be-remembered stimuli. Although no formal analyses of a quadratic trend were conducted, Sherman et al. (2003) showed z-ROC curves that appeared curvilinear for their control participants in a study of the effects of scopolamine on recognition performance. Secondary analyses of another study that used identical study materials as those used here with a slightly different procedure (Schwartz et al., 2005) also showed curvilinear z-ROC curves (Howard, 2005). Travel pictures not only are perceptually detailed stimuli, but also undoubtedly provide a rich combination of semantic information as well. Moreover, the particular travel pictures used in this experiment were likely to be completely novel to the participants, whereas words are experienced in a wide variety of preexperimental contexts. It is tempting to speculate that these properties of travel pictures make them particularly easy to recollect, leading to the strong explanatory power of the YHT in these studies.

If recognition performance for travel pictures is well described by the YHT but not the NUV, and recognition performance for words is well described by the NUV but not the YHT, this does not necessarily indicate qualitatively different memory process for different types of materials. One can describe the YHT in some sense as a traditional signal-detection model (e.g., D. A. Norman & Wickelgren, 1969) in which the old-item distribution is bimodal, with those items that are recollected having infinite strength. This assumption is untenable under sufficiently stringent response criteria. For instance, if participants are offered a million dollars for every correct "no" response and no reward for every correct "yes" response, one can be reasonably well assured that participants will never say yes to a probe, no matter how vividly they remember it. If recollection is not associated with infinite strength, then how best to characterize the strength of old items?

To describe the recognition performance of subjects administered scopolamine, Sherman et al. (2003) proposed a generalization of the YHT in which recollected items did not simply have infinite strength; rather, recollection was assumed to give rise to a normal distribution of strengths. That is, if an item is recollected, the resulting strength is variable, presumably reflecting different degrees of recollected detail. This variable recollection model, although not formally identical, is closely related to the some-or-none model proposed to describe associative recognition by Kelley and Wixted (2001). The some-or-none model has been explored by Macho (2004) and applied to the effects of aging on associative recognition performance by Healy et al. (2005). One interesting feature of the variable recollection model is that it can generate z-ROC curves that are neither linear nor monotonically concave like those observed here. Imagine that the old-item strength distribution is bimodal, with one distribution of strength corresponding to familiarity and another corresponding to recollection. For the purposes of illustration, assume further that the two peaks of the old-item distribution are (very) widely spaced. As the ROC curve passes through the first (familiarity) peak, the ROC resembles that generated by the YHT. However, as the criterion becomes more conservative, it starts to approach the second (recollective distribution). The ROC now moves toward the origin as the hit rate begins to decrease. When examined in z-ROC space, the phase where the criterion approaches the first distribution is linear, in the same way that the right side of the YHT's z-ROC curve is linear. On the extreme left of the z-ROC curve, the z-ROC is also linear, but with a different slope. In between these two phases, there is a concave region, resulting in a zigzag shape. If the criteria used in the experiment are not sufficiently conservative to enter the second linear region, the z-ROC curves correspond closely to those predicted by the YHT. The ability to describe zigzag z-ROC curves was essential to describe the z-ROC curves obtained from participants administered scopolamine (Sherman et al., 2003).

The variable recollection framework includes the YHT as a special case and is sufficiently broad to be extremely difficult to distinguish from the NUV in practice. By turning down the variability on the recollective process in the variable recollection model, one recovers the YHT. When the difference between the recollected item distribution and the old familiarity-based distribution is small relative to the variability of the recollective distribution, the effect is similar to one broad old-item distribution, as would be obtained from the NUV. Perhaps the variable recollection model or the some-or-none model offers a means to simultaneously account for the nearly linear z-ROC curves typically obtained with item recognition of words and the curvilinear z-ROC curves that have been observed here with travel pictures as stimuli.

Aging, Recollection, and the Hippocampus

The present results provide support from the quantitative modeling of ROC curves from item recognition for a broad literature arguing that aging is associated with a preferential decrement in recollection (e.g., Jennings & Jacoby, 1997; Healy et al., 2005; Naveh-Benjamin, 2000; Naveh-Benjamin et al., 2003; Prull et al., 2006). Recent work has shed light on the possible neural basis that underlies this deficit in recollection. Theorists have for some time hypothesized that the hippocampus is particularly important in the recollective component of recognition performance (e.g., Aggleton & Brown, 1999; K. A. Norman & O'Reilly, 2003). Recent evidence from neuroimaging implicates the hippocampus proper in recollection (Davachi et al., 2003; Ranganath et al., 2004; Yonelinas, Otten, Shaw, & Rugg, 2005) and episodic memory more generally (Addis, Moscovitch, Crawley, & McAndrews, 2004; Gilboa, Winocur, Grady, Hevenor, & Moscovitch, 2004). Fortin et al. (2004) showed that ROC curves from rats performing an item-recognition task for odors were consistent with those predicted by the YHT. However, rats with lesions to the hippocampus generated ROC curves that were well predicted by an equal variance signal-detection model. There is, therefore, ample evidence that the hippocampus supports recollection. There is also ample evidence that normal aging is associated with a disruption of the hippocampal formation (for a recent review, see Rosenzweig & Barnes, 2003). Small, Chawla, Buonocore, Rapp, and Barnes (2004) argued on the basis of both functional neuroimaging and studies of gene expression that the changes in the hippocampal formation associated with aging were restricted to the dentate gyrus, a subregion of the hippocampal formation. Although aging is associated with physiological changes in the hippocampus and the hippocampus is implicated in recollection, the deficit observed in older adults' recollection is not necessarily a direct consequence of changes in the hippocampus proper. Older adults have well-documented changes in prefrontal regions (Head et al., 2004; Raz et al., 1997; West, 1996), and the frontal cortex and hippocampus may be closely linked physiologically (Hyman, Zilli, Paley, & Hasselmo, 2005; Siapas, Lubenov, & Wilson, 2005). Perhaps the changes in hippocampal function presumed to underlie the deficit in recollection for older adults are actually a consequence of changes in prefrontal functioning.

The present results also suggest that the recollective process observed in item recognition is analogous to the recovery of temporal context hypothesized to support episodic associations in recall (Howard, Fotedar, Datey, & Hasselmo, 2005; Howard & Kahana, 2002). Howard, Wingfield, and Kahana (in press) fit the temporal context model to associative functions from free recall of random word lists of young and older adults (Kahana et al., 2002). They found that the deficit in temporally defined associations observed with aging was well described by allowing the parameter controlling item-to-context binding to be lower for older adults. Howard et al. (2005) hypothesized that this parameter is a function of the hippocampus proper and used this hypothesis to describe neuropsychological findings (Bunsey & Eichenbaum, 1996). There is also evidence that recollection in item recognition is associated with recovery of temporal context. Schwartz et al. (2005) showed that when a test item is recollected, memory for following test items is enhanced if those test items were from nearby serial positions. Taken together, these data suggest that the mnemonic deficit in aging is associated with a decrease in the ability of the hippocampus to enable binding of items to the temporal–spatial context in which they were presented.

Conclusion

We studied item recognition of travel pictures in young and older adults. We collected multiple confidence levels to enable the construction of ROC curves. Overall levels of accuracy were comparable for the young and older adults used in this study. We found evidence for nonlinear z-ROC curves in item recognition for both young and older adults, suggesting than the NUV account of recognition performance did not describe the data. Indeed, the YHT provided a better fit to the observed response distributions. Estimates of recollection were significantly higher for young than older adults. Estimates of familiarity were higher for older adults than for young adults, although the difference was not significant. This finding, coupled with other recent work, supports the hypothesis that the deficit in episodic memory with aging is a consequence of a failure to bind items to the temporal–spatial context in which they are experienced, a function that is probably dependent on the integrity of the hippocampus.

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