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Aging Effects on Recollection and Familiarity: The Role of White Matter Hyperintensities

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Abstract

Previous studies have indicated that aging is associated with declines in recollection whereas familiarity-based recognition is left largely unaffected. The brain changes underlying these recollection declines are yet not well understood. In the current study we examined the role of white matter integrity as measured by white matter hyperintensities (WMH) on age-related changes in recollection and familiarity. Recognition was measured using a remember/know procedure (Experiment 1) and a source-memory process-dissociation procedure (Experiment 2). Robust age related declines in recollection were observed, but there was no evidence that white matter damage was related to the observed memory declines. Although future studies with larger samples will be necessary to fully characterize the role of WMH in normal age-related declines in different types of memory, the results suggest that declines in recollection are not strongly related to the brain changes indexed by WMHs.

Keywords

Recognition memory; Aging; Recollection; Familiarity; White matter

INTRODUCTION

Recognition memory judgments can be based on the recollection of qualitative details of a previous event or on assessments of the familiarity of the test items (Jacoby, 1991; Rotello, Macmillan, & Reeder, 2004; Wixted, 2007; Yonelinas, 2002). Normal aging leads to deficits in recollection-based recognition, whereas familiarity-based recognition remains relatively

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intact (Light, Prull, La Voie, & Healy, 2000; Prull, Dawes, Martin, Rosenberg, & Light, 2006; Yonelinas, 2002). Although a number of studies have investigated the brain regions that support recollection and familiarity, relatively few have investigated the neural mechanisms underlying recollection deficits found in older adults. These studies have suggested either that recollection deficits are related to deteriorating frontal/executive function or medial temporal lobe function (e.g., Daselaar et al., 2006; Davidson & Glisky, 2002; Yonelinas et al., 2007)

Recent structural neuroimaging work has indicated that damage to white matter, as measured by white matter hyperintensities (WMH), is directly related to age-related declines in cognitive functioning. WMH appear on magnetic resonance images (MRI) as hyperintense regions in white matter areas and have been shown to reflect abnormalities such as demyelination, gliosis, and/or loss of axons (Fazekas et al., 1993). The appearance of WMHs with increasing age is quite prevalent (DeCarli et al., 2005; Yoshita et al., 2006) and is related to various health factors like hypertension, high cholesterol, heart disease, and diabetes (Breteler et al., 1994; DeCarli et al., 1995). Age related WMHs are more prominent in anterior than posterior brain regions (Pfefferbaum, Adalsteinsson, & Sullivan, 2005), and an increasing WMH load has been shown to be related to declines in free recall and executive functioning (Au et al., 2006; DeCarli et al., 1995; Gunning-Dixon & Raz, 2000; Nordahl et al., 2005; Van Petten et al., 2004). Notably, these effects have been observed in both large and small samples (e.g., *n* values range from 1820 to 15), suggesting that the effects of WMH load can be quite substantial. However, no study has yet examined the relationship between WMH and recollection, so it is not known whether white matter changes are related to the age-related declines observed in recollection.

Thus, the primary aim of this study was to investigate whether WMH load is associated with age-related recollection deficits commonly observed in tests of recognition memory. Toward this end, we measured recollection and familiarity in young control subjects and in older adults who had either high or low WMH loads. In Experiment 1 we examined recognition using a remember/know procedure, wherein subjects indicated whether their recognition judgments reflected memory of qualitative details (recollection) or a feeling of familiarity without memory of specific details (familiarity). The experiment was based on the memory-for-foils paradigm (e.g., Jacoby, Shimizu, Velanova, & Rhodes 2005b), designed to examine retrieval orientation effects. Young adults have been shown to process foil items on recognition tests in ways specific to the study context, such that their memory is better for foils on a test of deeply processed, compared to shallowly processed, items. In contrast, older adults do not show this effect, indicating that they do not process test items differently depending on the relevant study conditions. Our goals for this experiment were to examine the specific memory processes underlying this effect (i.e., recollection and familiarity) and to determine whether WMH load influences this effect within a group of older adults.

In Experiment 2 we examined recognition using a source-memory process-dissociation paradigm in which subjects were asked to remember each items' specific encoding conditions. Subjects encoded words in deep and shallow incidental conditions as well as in an undirected intentional condition. Our goal was to determine whether the intentional encoding condition would result in disproportionate age-related deficits in recollection (or familiarity) in comparison to the deficits found in the shallow or deep encoding conditions and whether any such age-related differences would be modulated by WMH load.

METHODS

Participants

Older adults between the ages of 65 and 80 were recruited from the UC Davis Alzheimer's Disease Center (ADC) based on previous assessment of WMH load. All participants had received a clinical diagnosis through the ADC of normal cognition, questionable cognitive impairment, or mild cognitive impairment based on neurological exams and neuropsychological evaluations. Only individuals in the ADC's pool who had at least 12 years of education, were dementia-free at the time of assessment and could speak English fluently were selected from the larger ADC database. MCI diagnosis was not used as a selector criterion and thus both individuals with and without MCI were included in the sample. Those participants were sorted according to WMH load (see below for quantification detail) with the highest and lowest selected as potential participants to be recruited for the current study. Twenty two older adults from this pool agreed to participate, however five participants from the high WMH group and one from the low group were excluded, resulting in 17 older adults, with nine in the low and eight in the high WMH groups. The five participants were excluded due to recent dementia diagnosis (1 high), recent stroke (1 high), misunderstanding of response options and/or inappropriate use of them (1 low, 1 high), and an inability to complete the tests (1 high). Young adult participants were undergraduates at UC Davis who participated in return for course credit. Demographic information on these three groups is presented in Table 1. The high and low groups did not differ with respect to age ($t(15) = -0.804$, $SE = 2.30$, $p = .434$) or education ($t(15) = -1.495$, $SE = 1.22$, $p = .156$).

WMH Quantification

Analyses of brain and WMH volumes were based on a Fluid Attenuated Inversion Recovery (FLAIR) sequence designed to enhance WMH segmentation (Jack et al., 2001). Images were orientated parallel to a hypothetical line connecting the Anterior Commissure (AP) and Posterior Commissure (PC).

Brain and WMH segmentation was performed in a two-step process according to previously reported methods (DeCarli et al., 1992, 1999). In brief, non-brain elements were manually removed from the image by operatorguided tracing of the dura matter within the cranial vault including the middle cranial fossa, but excluding the posterior fossa and cerebellum. The resulting measure of the cranial vault was defined as the total cranial volume (TCV) to correct for differences in head size amongst the subjects. Image intensity nonuniformities (DeCarli, Murphy, Teichberg, Campbell, & Sobering, 1996) were then removed from the image and the resulting corrected image was modeled as a mixture of two Gaussian probability functions with the segmentation threshold determined at the minimum probability between these two distributions (DeCarli et al., 1992). Once brain matter segmentation was achieved, a single Gaussian distribution was fitted to the image data and a segmentation threshold for WMH was *a priori* determined at 3.5 *SD*s in pixel intensity above the mean of the fitted distribution of brain parenchyma. Morphometric erosion of two exterior image pixels was also applied to the brain matter image before modeling to remove the effects of partial volume CSF pixels and ventricular ependyma on WMH determination. Intra and inter rater reliability for these methods are high and have been published previously (Decarli et al., 2005). Segmented and normalized (to cranial volume) WMH loads are reported in Table 1 for the older adult groups.

Materials and Procedures

Participants completed several behavioral tests in a 2-h test session. Subjects first completed Experiment 1 which was a memory-for-foils study (Jacoby et al., 2005b; Jacoby, Shimizu, Daniels, & Rhodes, 2005a), followed by several neuropsychological tests that included the Stroop Neurospychological Screening Test (Trennery, Crosson, DeBoe, & Leber, 1989), Trails A and B (Reitan, 1992), the d2 Concentration Test (Brickenkamp & Zillmer, 1998), Pattern comparison (Salthouse & Babcock, 1991), and Shipley IQ (Shipley, 1986). Finally they completed Experiment 2, the source memory study.

In the memory-for-foils experiment, subjects first encoded a list of 36 critical words in the shallow condition under instructions to indicate whether or not each word contained the letter

O or U by pressing keys labeled ‘yes’ and ‘no’. A standard old/new recognition test with the 36 old and 36 new words followed immediately. Subjects encoded a second study list under deep processing instructions to categorize each word as pleasant or unpleasant, and were then given another standard recognition test including the 36 old deep words and 36 new words. Both study lists and both tests included 2 primacy and 2 recency buffers. Two more tests, examining memory for the foils (new words) from the previous recognition tests, were administered. The first was a remember-know recognition test with the 36 foils that had appeared on the shallow recognition test and 36 new words, and the second was a similar recognition test for the foils that had appeared in the test of the deeply processed words. For each item on the remember-know tests, subjects responded ‘recollect’ if they could remember a specific detail of the word’s presentation on the previous test, ‘familiar’ if they recognized the word but could not remember anything specific about it, and ‘new’ if they did not recognize the word. Words were presented in a fixed order and assignment to condition; they were three to eight letters in length and were between 50 and 707 occurrences per million in frequency, with an average of 134 (Kucera & Francis, 1967); frequency was balanced across stimulus condition.

In the second phase of the study, participants completed the neuropsychological tests listed above. The Stroop, Trails, d2 Concentration and Shipley tests were administered according to the standard instructions and the Pattern Comparison test was administered according to instructions described by Salthouse and Babcock (1991).

The final phase of the study was the source experiment, which also included a levels-of-processing manipulation. Subjects were presented with words on a computer screen under deep or shallow incidental encoding conditions in three blocks (40 words in a deep block, 80 words in a shallow block, 40 words in a deep block). In the deep encoding task, subjects categorized the words as concrete or as abstract (by pressing the ‘c’ or ‘a’ keys). The shallow task required subjects to count the number of syllables in each word and enter that value using the keyboard. Next, an intentional study list of 60 words was presented auditorally without any processing instructions; the experimenter read a list of words at a rate of one every 2 s. Subjects were then given a source recognition test in which they were presented with the 120 old (deep, shallow, and heard) and 80 new items and asked to decide for each whether it was old or new. If they responded old, they were then asked to decide if it was ‘heard’, ‘seen’ (i.e., in the deep or shallow task), or if they were ‘unsure’ of its source. This test allowed estimates of recollection and familiarity to be generated using the equations of the process dissociation procedure (Jacoby, 1991, 1998). Recollection was estimated as the ability to remember whether an item was presented in the visual or auditory lists, and familiarity was estimated as the ability to recognize the item as old given it was not recollected. Words were presented in a fixed order and assignment to condition; they ranged from three to nine letters in length and from 50 to 660 occurrences per million in frequency.

RESULTS

Alpha was set at .05 unless otherwise noted and effect sizes (Cohen’s *d* and partial eta squared, η^2) are reported for significant findings as well as important but non-significant findings.

Measures of White Matter

Figure 1 presents the average measures of WMH in cubic centimeters in the high and low WMH groups. The figure indicates the high load group exhibited a WMH load that was approximately five times that of the low load group, $t(15) = -6.106$, $SE = 1.332$, $p < .001$, $d = 2.78$. To accommodate variation in overall brain volume, we also examined WMH volumes normalized for total cranial volume. Consistent with the raw volume measures, the high group had relative volumes that were five times that of the low load group, 0.97 vs 0.19%; $t(15) = -6.026$, $SE = .001$, $p < .001$, $d = 2.70$.

Neuropsychological Tests

In general, the older adults were lower on measures of executive function than the young subjects, but did not differ on measures of verbal ability or intelligence. In addition, the high WMH group exhibited slightly lower scores than the low WMH group, but the differences were not significant. Table 1 shows performance of the three groups on the neuropsychological measures. Ink naming on the Stroop test was more difficult for all subjects than was word reading, but that difference was larger for the older adults than the young adults, $F(2, 33) = 32.35$, $MSE = 126.33$, $p < .001$, $\eta^2 = .662$, and did not differ between the two WMH groups ($p > .99$, $d < 0.47$) . Performance on the other measures followed a similar pattern. Pattern comparison proved a more difficult task for older than for younger adults, but did not differ between the WMH groups, $F(2, 33) = 23.12$, $MSE = 12.08$, $p < .001$, $\eta^2 = .584$; high and low WMH vs. young $p < .001$, $d > 1.90$; high vs. low WMH $p > .99$, $d = 0.17$. Concentration performance as measured on the d2 test was approximately the same for the high and low WMH groups, both of which had lower scores than the young adults, $F(2, 33) = 16.439$, $MSE = 2260.62$, $p < .001$, $\eta^2 = .50$; high and low WMH vs. young $p < .001$, $d > 1.05$; high vs. low WMH $p > .99$, $d = 0.23$. Trail Making performance was analyzed as the difference between RTs on Trails A and Trails B; the main effect of group was marginal when older adults were split into high and low WMH groups and no differences appeared between any of the subgroups; however an age-related difference favoring the young was found when the older adult groups were collapsed, $F(1, 35) = 5.59$, $MSE = 717.91$, $p < .03$, $\eta^2 = .758$. Performance on Shipley vocabulary did not differ among the groups when high and low WMH were treated separately but did show the typical aged-advantage when the WMH groups were collapsed ($t(35) = -2.22$, $p < .04$, $d = 0.71$). Performance on the Shipley reasoning task differed among groups, $F(2, 34) = 16.24$, $MSE = 46.19$, $p < .001$, $\eta^2 = .920$, but only between each of the WMH groups and the young adults ($p < .002$, $d > 1.75$). Shipley IQ scores did not differ among the groups ($F < 1$).

Experiment 1: The Memory-for-Foils Remember/Know Experiment

The proportion of recollect (remember) and familiar (know) responses for each group are presented in Table 2. Recollection was measured as the proportion of recollect responses to studied items, minus the proportion of recollect responses to nonstudied items (new foils). Familiarity was estimated as the proportion of familiar responses given that the item was not recollected for both old and new items (Yonelinas & Jacoby, 1995), and familiarity for new items was subtracted from familiarity for old items to create the final familiarity estimate. Two (deep vs. shallow) by three (subject group) mixed design ANOVAs were used to separately evaluate recollection and familiarity estimates.

Figure 2A presents the estimates of recollection and familiarity for shallow and deep lists for each subject group. A significant effect of group on recollection, $F(2, 34) = 10.18$, $MSE = 0.018$, $p < .001$, $\eta^2 = .37$, arose because both aged groups exhibited significantly lower recollection estimates than the young adults (high and low WMH vs. young $p < .001$, $d > 1.00$). However, recollection did not differ between the high and low WMH groups ($p > .99$, $d = 0.34$). There was also a significant condition by group interaction, $F(2, 34) = 7.74$, $MSE = 0.007$, $p < .003$, $\eta^2 = .235$, reflecting the fact that for the young subjects recollection was greater for deep lures than the shallow lures, whereas the older groups were not sensitive to the deep/shallow manipulation. The latter finding indicates that neither of the older groups exhibited evidence of the retrieval orientation effects observed in the young subjects. There was also a significant effect of group on familiarity, $F(2, 34) = 9.67$, $MSE = 0.021$, $p < .001$, $\eta^2 = .36$, reflecting lower familiarity estimates in older than younger subjects. The two WMH groups did not differ from one another ($p = .24$, $d = 0.93$), but the familiarity reduction in the high WMH group was significant ($p < .001$, $d = 1.65$) whereas the reduction in the low WMH group did not quite reach the level of significance ($p = .09$, $d = 0.97$).

In sum, the aged subjects exhibited recollection deficits relative to the young subjects, but the high vs. low WMH groups did not differ from one another. Thus, there was no evidence that the recollection deficits associated with aging were related to WMHs. Familiarity was also somewhat reduced in the aged subjects, and although the high load group had slightly lower familiarity estimates than the low load group, the high and low WMH groups did not differ significantly from one another. In addition, the retrieval orientation effects (i.e., better recognition for foils tested in the deep condition than those tested in the shallow condition) were only observed in the recollection-based responses in the young subjects, indicating that the older subjects failed to orient to study contexts during retrieval in the same way as the younger subjects did. Importantly, however, these orientation effects were no more apparent in the low WMH group than the high WMH group. So, although age-related declines in recollection may be related to a failure to orient appropriately during retrieval, the presence of WMH does not appear to modulate this effect.

Experiment 2: The Source Memory Process Dissociation Experiment

In the source memory experiment, recollection and familiarity estimates were derived using the process-dissociation method (Jacoby, 1991, 1998); inclusion and exclusion scores were calculated for each participant based on their source recognition responses and then were transformed into proportional recollection and familiarity estimates. Recollection and familiarity estimates were proportions, and were corrected for false recollection and false familiarity, respectively. Both recollection and familiarity were submitted to three (encoding task) × three (participant group) mixed design ANOVAs.

Raw responses are presented in Table 3 and Figure 2B presents estimates of recollection and familiarity for each group. For recollection, main effects of both encoding task and subject group were found [encoding: $F(2, 66) = 25.30$, $MSE = 0.011$, $p < .001$, $\eta^2 = .43$; group: $F(2, 33) = 10.39$, $MSE = 0.02$, $p < .001$, $\eta^2 = .39$]. Follow up tests showed that young adults had higher recollection estimates than both WMH groups ($p < .01$, $d > 1.10$). Numerically, the low WMH group had greater recollection estimates than the high WMH group in all three conditions, but the difference did not approach significance ($p > .99$, $d = 0.38$). Deep encoding led to the highest recollection estimates followed by the intentional, then the shallow encoding conditions in all groups.

For familiarity, the main effect of encoding task was significant, $F(2, 66) = 10.91$, $MSE = 0.011$, $p < .001$, $\eta^2 = .248$ with deep processing leading to higher familiarity than either of the other two conditions. There was no significant effect of subject group on familiarity, $F(2, 33) = 1.75$, $MSE = 0.029$, $p = .189$, $\eta^2 = .10$, although a marginal effect of age emerged when the WMH groups were collapsed, $F(1, 34) = 3.51$, $p = .07$, $\eta^2 = .09$.

In sum, the source memory experiment showed that recollection was reduced in the aged subjects relative to the young subjects, whereas familiarity was relatively preserved. Although recollection was numerically higher for the low than high WMH group, the difference did not approach significance. There was no indication that WMH influenced familiarity. Finally, the aging decrements in recollection were comparable across the incidental and intentional conditions, indicating that the memory impairments were not related to the nature of the encoding instructions.

DISCUSSION

This study examined whether the age-related declines in recollection could be attributed to white matter injury, as measured by global WMH volume. In Experiment 1 we used a remember/know procedure to measure recollection whereas in Experiment 2 we used a source memory procedure. Recollection, in both experiments, was significantly disrupted in the older subjects relative to the young subjects, but recollection in the aged subjects with high WMH loads did not differ from those with low WMH loads. In the source memory experiment, the recollection estimates were numerically greater for older adults with low compared to high WMH loads, but this difference did not approach significance. Moreover, in the remember/know experiment there was no indication that white matter load influenced recollection. Thus, the results of the two experiments provide little support for the hypothesis that age-related decreases in recollection can be explained by increases in white matter hyperintensities in the aged subjects.

A critical limitation of the current study is that the samples sizes were not large. Thus the current results cannot be interpreted as indicating that WMH has no effect on recollection. With larger samples it is quite possible that WMH effects might emerge. In fact, a recent meta-analysis suggested that the effects of WMH on standard memory measures are significant but small (Gunning-Dixon & Raz, 2000). Nonetheless, the current results are informative about the role that WMHs likely play in the recollection declines typically seen in normal aging. The aging effects on recollection that we observed were quite large, in the sense that across the studies aging reduced recollection from about .31 to .12, an absolute difference of .19. In contrast, the WMH effect was very small; across studies higher WMH load reduced recollection from about .13 to .10, an absolute difference of only .03. The results show that the aging effects we observed on recollection could not have been caused entirely by WMH. Additionally, the high and low white matter groups were selected using an extreme-groups design. That is, the low WMH group had a WMH load of .19% of total cranial volume whereas the high WMH group had a WMH load that was .97% of their total cranial volume, nearly five times that of the low group. It is unlikely that the aged groups in standard studies of aging would have had a white matter load as high as that seen in the high WMH group in the current study.

Under what conditions do WMHs influence memory performance? One potentially important factor is that the WMH groups in the current study had very high levels of education (i.e., an average of over 16 years of formal education and only two subjects who had no education past high-school). Level of education has been shown in previous studies to have a protective effect, such that those with higher levels of education are more resistant to the deleterious cognitive consequences of neurological disease and injury (Bennett et al., 2003; Nebes et al., 2006; Satz, 1993; Stern, 2002). Whether white matter changes may have larger effects on recollection and or familiarity-based recognition in a more diverse group of older adults is an important question for future studies.

White matter changes may also play a more important role in memory tests that rely more heavily on executive control processes. For example, WMH load has been found to affect free recall performance (e.g., Petkov et al., 2004). Free recall seems likely to share underlying component processes with recollection as measured in remember/know and source memory testes, but free recall may be more dependent on regions of the prefrontal cortex due to the heavy working memory load (e.g., self-cueing, organization, attentional constraint, etc.) whereas recollection in recognition tasks may place lesser demands on prefrontal areas and executive functions (e.g., cueing is provided, organization and constraint of attention to context are often easier). Further work examining the contributions of WMHs in other memory tasks that differ in their executive processing demands will be useful.

In addition to the WMH results, the age-related differences found in the current experiments are also informative. Experiment 1 was designed to investigate aging effects on retrieval orientation and specifically on the depth-of-retrieval effect (e.g., Jacoby et al., 2005b). As expected, only the young adults showed a depth-of-retrieval effect, indicating that young adults processed test items in manners specific to the study contexts whereas older adults did not. In addition, the retrieval orientation effect was found only in the recollection estimates, suggesting that depth-of-retrieval effects may generally be driven by recollection.

Experiment 2 was designed to investigate the role of intentional versus incidental encoding in age-related differences in memory. Typical age-related differences were observed but the pattern of performance across the different encoding conditions was the same for the two age groups. Specifically, recollection and familiarity estimates in the intentional (unsupported) condition fell in between those in the shallow and deep encoding conditions for both age groups. Thus, encoding support, or lack thereof, does not appear to have been a major factor in the age-related declines in recollection or familiarity in this paradigm.

Overall, this study found no evidence for WMH as an explanation of normal age-related declines in recollection. Of course, at extreme levels WMH load is likely to have an effect, although extreme WMH burden is more typically associated with dementia or MCI than with healthy aging. However, given the ranges studied here and the minimal effects observed, it appears that recollection declines found in normal aging are unlikely to be explained by differences in WMH load. These data thus suggest that within normal ranges found in relatively healthy populations, disruptions in communication between different brain regions (i.e., prefrontal and more posterior regions given the typical distribution of WMH) do little to explain age-related declines in recollection and familiarity.

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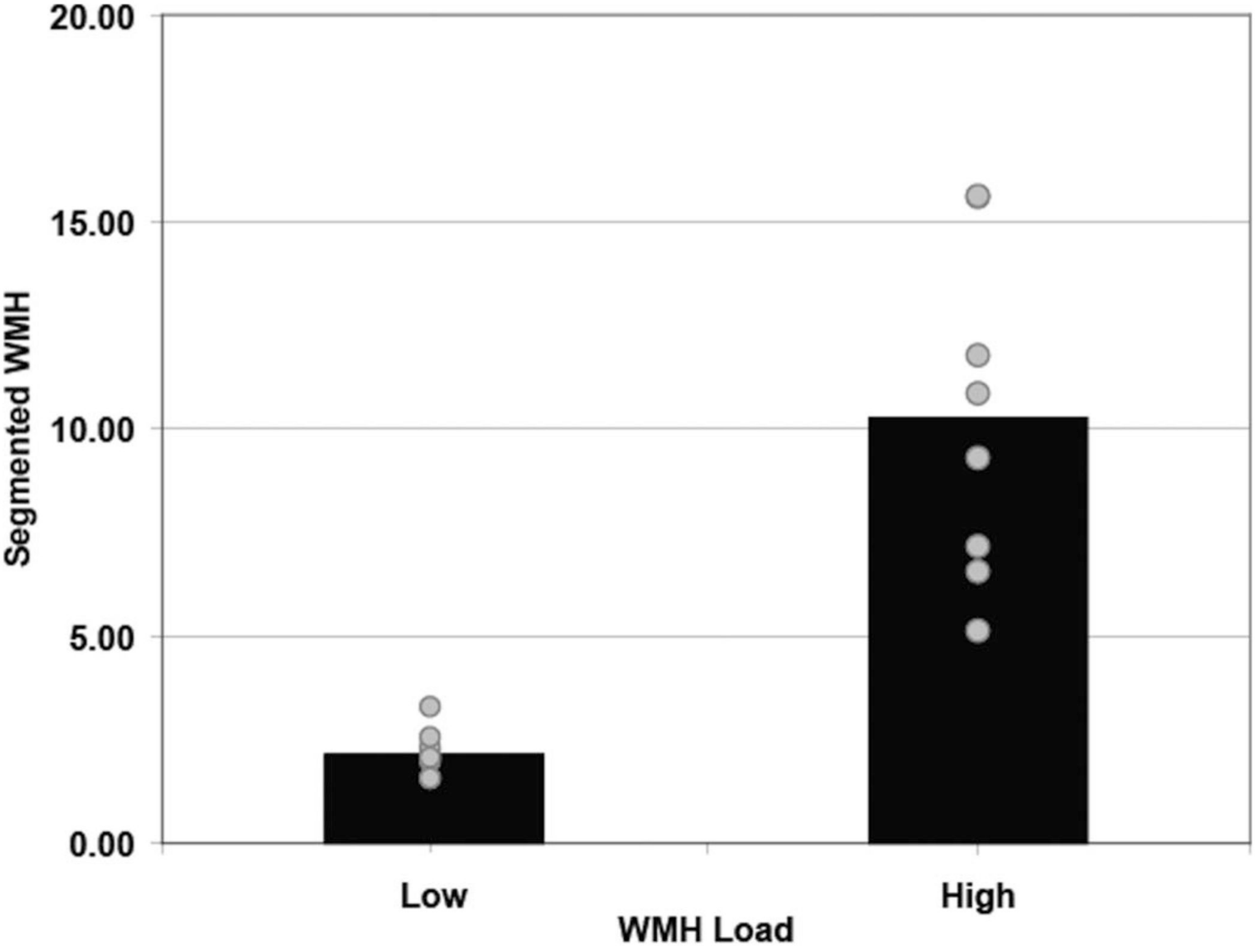

FIGURE 1.

Segmented white matter hyperintensity (WMH) in cubic centimeters (cc) for the low and high WMH groups. Grey circles represent WMH load in individual subjects in each group.

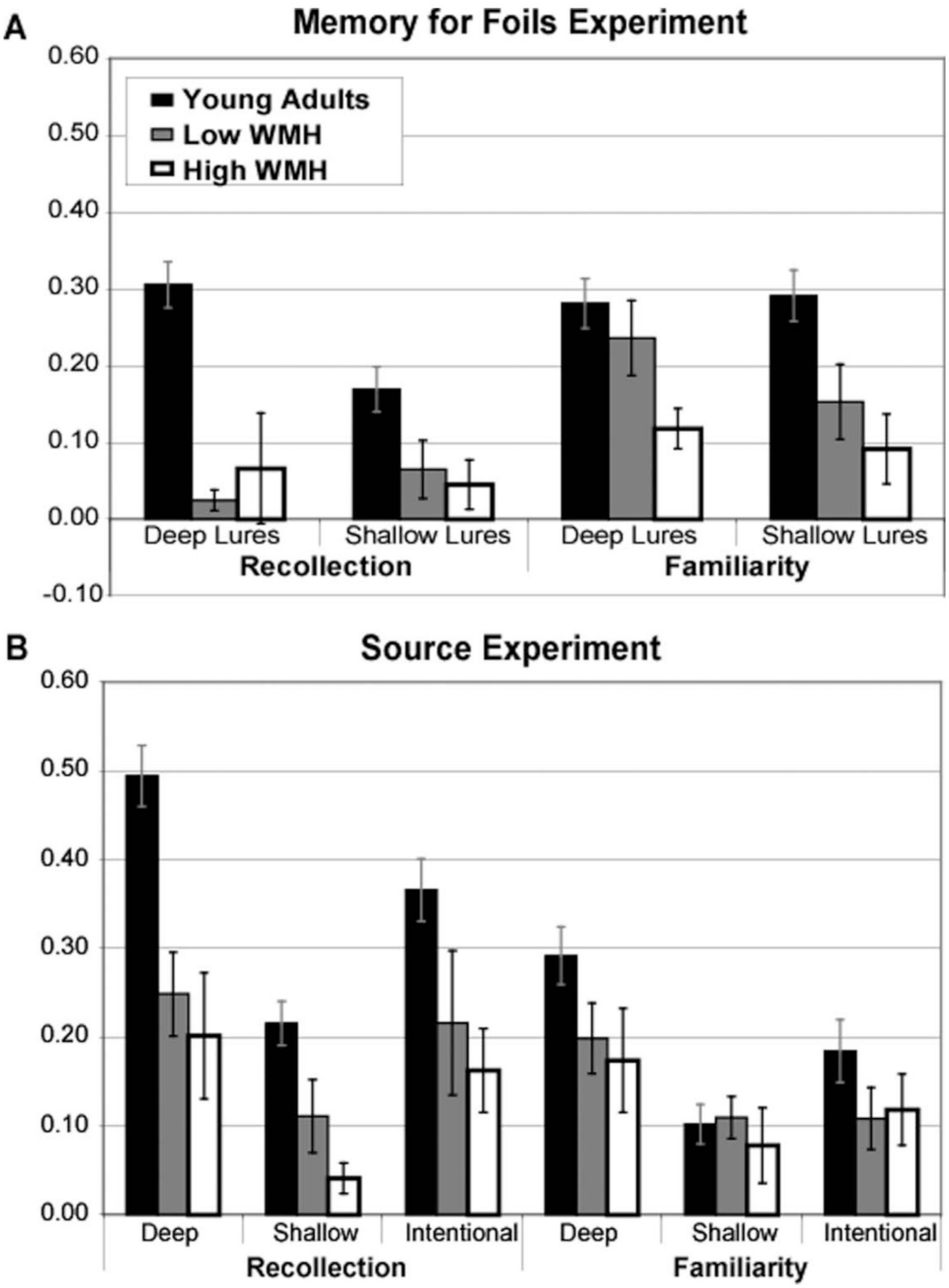

FIGURE 2.

(Panel A) Recollection and familiarity estimates in the RK memory-for-foils experiment. Recollection estimates are accurate recollect response proportions minus false recollect response proportions. Familiarity estimates are IRK familiarity estimates for old items, corrected for familiarity for new items. (Panel B) Recollection and familiarity estimates in the source experiment. Both recollection and familiarity estimates are corrected for false recollection and familiarity, respectively.

TABLE 1

Demographic and Neuropsychological Characteristics

	Young Adults	**Older Adults (WMH Collapsed)**	**High WMH**	**Low WMH**
Demographics				
n	20	17	8	9
Age	18.90 (.85)	72.4 (4.60)	73.6 (3.81)	71.2 (51.4)
Education	12.8 (.83)	16.41 (2.59)	17.4 (2.60)	15.6 (2.50)
WMH load (segmented)		5.97 (4.96)	10.27 (3.97)	2.14 (.53)
WMH load (normalized)		0.0056 (.0047)	0.0097 (.004)	0.0019 (.0006)
MCl n		7 (+ 3 questionable)	4 (+ 2 questionable)	3 (+ 1 questionable)
Neuropsychological Tests				
Pattern Comp.	21.825 (3.85)	13.91 (2.81)	14.21 (3.53)	13.67 (2.30)
d2 Conc.	212.95 (39.23)	122.00 (55.47)	130.00 (76.51)	115.78 (35.78)
Stroop				
Word Reading	111.85 (.49)	110.63 (3.24)	109.71 (4.39)	111.33 (2.00)
Ink Naming	9.45 (16.11)	50.56 (17.16)	46.57 (15.76)	53.67 (18.47)
Trials				
A	25.3 (6.51)	43.18 (24.12)	51.50 (33.05)	35.78 (8.80)
B	61.1 (22.34)	99.88 (48.62)	107.38 (56.15)	93.22 (43.17)
Shipley				
Vocabulary	29.35 (3.54)	32.71 (5.58)	33.25 (6.50)	32.22 (4.97)
Reasoning	32.4 (4.71)	19.76 (8.60)	21.25 (8.00)	18.44 (9.37)
IQ	107.05 (7.67)	108.69 (14.01)	112.29 (15.60)	105.89 (12.87)

Note: WMH, white matter hyperintensity; MCI, mild cognitive impairment; questionable indicates a diagnosis of ‘questionable cognitive impairment’. Segmented WMH is in cubic centimeters. Normalized WMH load is a proportional measure of segmented WMH out of total cranial volume. Pattern Comp., Pattern comparison scores are the average scores across two tests, each with a maximum possible score of 30. d2 Conc., the d2 Concentration score reflects performance on a speeded visual attention task in which perfect performance would result in a score of 299. Stroop word reading and ink naming are correct trials, ranging from 0 to 112. Trails A and B scores are RTs in seconds to complete each test. Shipley vocabulary and reasoning range from 0 to 40. Shipley IQ is computed from vocabulary and reasoning scores.

TABLE 2

Experiment 1 (Memory for Foils) Raw Responses

	Shallow						Deep					
	Old Foils (Targets)			**New Foils (False Alarms)**			**Old Foils (Targets)**			**New Foils (False Alarms)**		
	Recollect	**Familiar**	**New**	**Recollect**	**Familiar**	**New**	**Recollect**	**Familiar**	**New**	**Recollect**	**Familiar**	**New**
Young Adults	.22 (.14)	.38 (.14)	.40 (.15)	.05 (.06)	.18 (.11)	.77 (.15)	.36 (.17)	.30 (.13)	.34 (.17)	.05 (.08)	.18 (.17)	.77 (.21)
Older Adults (WMH collapsed)	.09 (.14)	.39 (.23)	.53 (.25)	.04 (.06)	.28 (.28)	.68 (.29)	.09 (.15)	.35 (.21)	.56 (.19)	.05 (.09)	.18 (.14)	.77 (.14)
High WMH	.09 (.15)	.25 (.19)	.66 (.17)	.05 (.09)	.16 (.14)	.79 (.17)	.14 (.20)	.27 (.20)	.59 (.16)	.08 (.13)	.17 (.16)	.75 (.15)
Low WMH	.09 (.14)	.49 (.22)	.42 (.26)	.03 (.03)	.39 (.33)	.58 (.35)	.05 (.04)	.42 (.21)	.53 (.13)	.02 (.04)	.20 (.12)	.78 (.13)

Note: Recollect and familiar were terms used for ‘remember’ and ‘know’, respectively. Data are mean proportions with standard deviations presented in parentheses. Old foils were items that had served as foils on one of the first two recognition tests (one test each for shallow and deep), but as targets on the final memory-for-foils tests. New foils were words which had not appeared yet in any phase of the experiment.

TABLE 3

Experiment 2 (Source Memory) Raw Responses

	Shallow (seen)				Deep (seen)				Heard				New			
	Seen	**Heard**	**Unsure**	**New**	**Seen**	**Heard**	**Unsure**	**New**	**Seen**	**Heard**	**Unsure**	**New**	**Seen**	**Heard**	**Unsure**	**New**
Young	.34 (.12)	.05 (.06)	.08 (.09)	.52 (.14)	.62 (.16)	.06 (.07)	.09 (.09)	.23 (.11)	.13 (.09)	.40 (.15)	.09 (.10)	.37 (.14)	.13 (.09)	.04 (.05)	.06 (.06)	.06 (.11)
Older (WMH collapsed)	.18 (.18)	.12 (.13)	.14 (.14)	.42 (.20)	.30 (.24)	.12 (.11)	.15 (.16)	.35 (.25)	.10 (.11)	.24 (.24)	.15 (.16)	.39 (.23)	.09 (.12)	.09 (.10)	.11 (.13)	.53 (.17)
High WMH	.09 (.10)	.11 (.13)	.16 (.15)	.64 (.12)	.25 (.25)	.11 (.12)	.17 (.16)	.46 (.21)	0.6 (.06)	.25 (.18)	.15 (.20)	.53 (.17)	.05 (.05)	.09 (.12)	.10 (.13)	.77 (.13)
Low WMH	.27 (.19)	.12 (.13)	.11 (.14)	.51 (.23)	.41 (.22)	.12 (.11)	.10 (.16)	.37 (.28)	.17 (.12)	.28 (.29)	.09 (.13)	.46 (.28)	.16 (.14)	.07 (.08)	.10 (.13)	.68 (.20)

Note: Data are mean proportions of each response type (seen, heard, unsure, new) to each stimulus type (shallow (seen), deep (seen), heard, and new) with standard deviations presented in parentheses beneath each mean.