Routes to remembering: the brains behind superior memory

Eleanor A. Maguire[1], Elizabeth R. Valentine[2], John M. Wilding[2] and Narinder Kapur[3]

[1] Wellcome Department of Imaging Neuroscience, Institute of Neurology, University College London, 12 Queen Square, London WC1N 3BG, UK

[2] Department of Psychology, Royal Holloway, University of London, Egham, Surrey TW20 0EX, UK

[3] Department of Clinical Neuropsychology, Wessex Neurological Centre, Southampton General Hospital and Department of Psychology University of Southampton, Southampton SO16 6YD, UK

Correspondence should be addressed to E.A.M. (e.maguire@fil.ion.ucl.ac.uk)

Why do some people have superior memory capabilities? We addressed this age-old question by examining individuals renowned for outstanding memory feats in forums such as the World Memory Championships. Using neuropsychological measures, as well as structural and functional brain imaging, we found that superior memory was not driven by exceptional intellectual ability or structural brain differences. Rather, we found that superior memorizers used a spatial learning strategy, engaging brain regions such as the hippocampus that are critical for memory and for spatial memory in particular. These results illustrate how functional neuroimaging might prove valuable in delineating the neural substrates of mnemonic techniques, which could broaden the scope for memory improvement in the general population and the memory-impaired.

Humans have an enduring fascination with memory. We are moved by the devastating effects of Alzheimer's disease on the one hand, and are often covetous of superior memory on the other. A testament to the latter is the interest throughout history in prodigious individuals renowned for spectacular mnemonic feats[1–3]. Despite its popular appeal, however, exceptional memory is seldom addressed in mainstream research[3–5], a fact which stands in contrast to the voluminous literature on memory loss. Although our understanding of the functional anatomy of human memory in the context of brain damage has certainly grown over the years, there have been far fewer attempts to explore the other end of the cognitive spectrum—those with superior memory.

One reason for the lack of interest may be that individuals with exceptionally good memories are in some way distinct, limiting the inferences that can be made about memory in the general population. However, it is equally possible that individuals with exceptional memory merely make more or better use of memory capabilities that we all possess, or perhaps they employ clever mnemonic devices or learning strategies[3]. Given that the basis of superior memory is still largely unknown, important insights into the structure of human memory may be missed by not exploring better-than-average memorizers as well as those with memory deficits. Moreover, understanding superior memory may also inform our efforts to improve memory in the general population and the memory-impaired. Some clues about the nature of superior memory can and have been gleaned from behavioral testing[3]. However, documenting the neural underpinnings would offer significant insights into the mechanisms of exceptional memory performance.

Expertise within specific knowledge domains (such as chess[6], calculation[7], and cars and birds[8]) has been examined previously with functional neuroimaging, but people with more generalized superior memory abilities have not been studied. Here we report the neural basis of memory in such individuals. Although exceptional individuals have been sporadically documented in the literature, they are more difficult to find than those with memory problems, who often seek advice. However, the World Memory Championships—a unique gathering of individuals performing exceptional memory feats across a range of tasks—is held annually in London[3,9]. We therefore examined eight participants who are or have been placed at the highest levels in the World Memory Championships, as well as two other individuals studied previously for their extraordinary memory accomplishments (see reports of TE and TM in ref. 3). The ten superior memorizers (SMs) were compared with ten matched control subjects who did not report any exceptional memory capabilities.

We set out to address three main questions. First, do SMs differ from control subjects in other intellectual abilities, which could drive the apparent superiority in memory functioning? Second, as there are reports of structural brain differences in groups with specific skills[10,11], are SMs predisposed to superior memory performance by virtue of having structurally different brains compared with control subjects, either innately or by developing their superior memory[10]? And finally, using functional magnetic resonance imaging (fMRI), we investigated if there were differences between SMs and controls in the brain areas engaged while processing incoming information. The present results show that superior memory was not due to exceptional intellect or to structural brain differences. Rather, we found that superior memory was associated with the preferential engagement of three brain regions in particular: medial parietal cortex, retrosplenial cortex and the right posterior hippocampus.

RESULTS
Neuropsychological testing
The superior memorizers were not exceptional in their perfor-

Table 1. Summary scores from standard neuropsychological measures.

	Superior memorizers ($n = 10$)		Controls ($n = 10$)	
Measure	Mean (s.d.)	Range	Mean (s.d.)	Range
Age (years)	33.90 (9.33)	22–53	33.10 (7.90)	20–46
Laterality quotient[a]	53.84 (46.11)	–68.42–86.67	49.14 (58.23)	–64.71–100
Years practicing mnemonics	11.10 (10.45)	3–38.5	–	–
NART (verbal IQ)[b]	111 (8.31)	95–119	112 (5.96)	98–119
Matrix reasoning[c]	12.90 (1.79)	9–16	12.40 (1.26)	10–14
Rey[d] figure				
copy	35.70 (0.67)	34–36	35.60 (0.52)	35–36
DR	21.60 (3.81)	17–29	22.70 (6.21)	13–33
Story[e]				
IR(**)	50.50 (3.78)	43–55	43.50 (6.47)	34–51
DR(*)	48.50 (7.79)	29–55	42.90 (6.28)	35–54
Digit span[f](***)	16.80 (2.49)	11–19	12 (2.21)	8–15
SMQ[g](*)	162.3 (22.72)	139–196	145.6 (15.58)	118–173

[a]Edinburgh Handedness Inventory[33]
[b]NART, the National Adult Reading Test, is an estimate of verbal IQ[34]; this test was not given to one SM whose native language is not English, contravening a requirement of the test.
[c]Scaled scores from the Matrix Reasoning subtest from the Wechsler Abbreviated Scale of Intelligence (WASI), a measure of non-verbal fluid reasoning and general intellectual ability[35].
[d]Rey complex figure, a visual reproduction and memory task (max score, 36); delayed recall (DR) was after 30 min[36,37].
[e]Story (verbal recall) from the Adult Memory and Information Processing Battery (AMIPB) (max score, 56); IR, immediate recall; delayed recall (DR) was after 30 min[38].
[f]Scaled scores from the digit span subtest of the Wechsler Adult Intelligence Scale Revised (WAIS-R)[39].
[g]Subjective Memory Questionnaire, where a higher score reflects the subjective impression of good memory[40,41].
Significant differences between groups:
*$P < 0.05$ one-tailed, **$P < 0.01$ two-tailed, ***$P < 0.001$ two-tailed.

mance on tests of general cognitive ability; they were in the high-average range in both general verbal and non-verbal skills, comparable to normal controls (**Table 1**). As expected, the SMs performed significantly better than control subjects on tests of working and long-term verbal memory, these tasks being similar to those commonly featured in memory competitions. The two groups did not differ on the measure of visual memory, perhaps owing to the fact that the SMs do not in general practice recall of visual patterns.

Structural brain imaging

Optimized structural MRI images of the brains of SMs and control subjects were compared for differences in gray matter volume using whole-brain voxel-based morphometry (VBM)[12]. For structural brain analysis, VBM has many advantages over region-of-interest (ROI) techniques in that it is automated rather than observer-based, and the whole brain is considered with no *a priori* regions of interest. VBM is sensitive to structural hippocampal changes in clinical[13] as well as non-clinical[10,14] subjects. For example, structural differences between the hippocampi of London taxi drivers and the general population have been reported[10]. Importantly, the MRI scans of the taxi drivers were not only analyzed using VBM, but they were also independently analyzed using the standard ROI approach focusing on the hippocampus. The findings from the two techniques were completely concordant, confirming the appropriateness of using VBM to study the hippocampus in non-clinical samples. Another study using VBM also reports hippocampal differences in a non-clinical context in relation to gender[14].

When the SMs and control subjects were compared, no significant differences were evident (either at a threshold of $P < 0.05$ corrected for multiple comparisons, or at the more liberal $P < 0.005$ uncorrected). Among the SMs, there were no changes in gray matter volume as a function of the number of years engaged in actively challenging their superior memory, or in relation to performance on the standard measures (**Table 1**) or later experimental measures (see below and **Table 2**). Although our samples were quite small, VBM changes have been detected in similar settings[10,13]. This result suggests that superior memory in the SMs is not associated with structural brain differences (that can be detected by VBM).

Functional brain imaging

As neither exceptional intellect nor gross structural brain differences seemed to relate to superior memory, we then used fMRI to index neural activity while subjects were learning new information. During scanning, the SMs and control subjects learned items that were presented visually (**Fig. 1**) and the order in which they were presented—tasks at which the SMs excel (see **Fig. 2** and Methods for task details). Imaging data were recorded during learning, and behavioral performance was measured for order and item recognition memory.

One potential confound with this fMRI protocol, given that SMs tend to perform better than control subjects, is that differences in brain activity may reflect the amount of information being successfully learned rather than the mechanisms underlying the cognitive process. To address this issue, we included three classes of stimuli in the fMRI study (**Fig. 1**). Three-digit numbers, which are items that the SMs particularly excel at learning, were expected to elicit a large performance difference between the two groups. The second stimulus type comprised faces, which are items that the SMs are excellent at learning but that can also be well retained by many individuals in the general population, so less of a difference was expected between the two groups. The final stimulus type was snowflakes[15], which are unusual and dif-

Table 2. Summary scores for the order and item memory tests.

Measure	Mean (s.d.)		
	Digits	Faces	Snowflakes
	Superior memorizers (*n* = 10)		
Order test[a] number correct	12.70 (2.75)	13.30 (2.06)	11.70 (2.00)
Recognition test[b] number correct	25.90 (2.85)	27.60 (2.76)	19.70 (1.70)
Recognition test[c] correct & confident	23.40 (4.01)	21.80 (6.44)	8.80 (5.25)
	Controls (*n* = 10)		
Order test[a] number correct	11.10 (0.99)	12.30 (2.79)	10.40 (1.76)
Recognition test[b] number correct	18.50 (3.06)	25.70 (3.27)	19.70 (4.67)
Recognition test[c] correct & confident	8.20 (4.52)	19.50 (6.52)	7.30 (5.10)

[a]From the order memory tests performed during scanning, maximum possible was 15; significant effect of stimulus type ($P < 0.01$), with the difference due to better performance on faces than snowflakes.
[b]From the post-scan forced-choice recognition tests, those correctly identified as seen during scanning, maximum possible was 30; significant effect of group ($P < 0.05$), with SMs better than controls, stimulus type ($P < 0.01$), with faces better than both digits and snowflakes, and significant interaction ($P < 0.01$), with digits better in SMs.
[c]From the post-scan forced-choice recognition tests, those correctly and confidently identified as seen during scanning; significant effect of group ($P < 0.01$), with SMs better than controls, stimulus type ($P < 0.001$), with faces better than both digits and snowflakes and digits better than snowflakes, and interaction ($P < 0.001$), with digits better in SMs. There were no significant reaction time differences, and no performance differences between groups for the control condition (where the range was 87–100% correct across all subjects).

Fig. 1. Examples of the stimuli. (**a**) Three-digit numbers were presented in black font in bold at a point size of 280. (**b**) Faces comprised black and white photographs of a face including hair; all were male, facing forward with neutral emotional expressions. (**c**) Snowflakes were white on a black background, taken from Bentley and Humphreys[15] and digitized (snowflakes reproduced with permission, Dover Publications Inc., New York).

ficult to verbalize; thus we expected little or no difference between the two subject groups for this stimulus type. This expected range of performance differences was indeed reflected in the data, with the greatest difference between groups seen for the digit stimuli, then faces and finally snowflakes. Thus we could differentiate brain activity that covaried with performance from activity that was associated with the learning process itself (irrespective of the amount of material being learned). The efficacy of learning, as measured by performance on the item order and recognition memory tasks, is detailed in **Table 2**.

fMRI analysis showed that several brain regions were active for all contrasts in both groups. To verify which brain regions were active in each subject for each contrast, we did a conjunction analysis (Methods). Briefly, by calculating the contrast for each stimulus type minus its control task, we removed low-level and stimulus-related visuo-perceptual factors. This showed that several brain regions were active in all subjects during the learning of all stimulus types. These included bilateral superior frontal sulcus (Talairach coordinates (*x, y, z*): −24, 12, 63; 30, 6, 60), left medial superior frontal sulcus (−3, 18, 45), bilateral caudate (−12, 12, 12; 12, 3, 15), left angular gyrus (−30, −72, 36) and bilateral cerebellum (−33, −57, −33; 33, −63, −33). In addition, the left middle occipital gyrus (−21, −90, −12) was active for all subjects for snowflakes only. The left posterior inferior frontal sulcus (−48, 15, 21) was active for both groups,
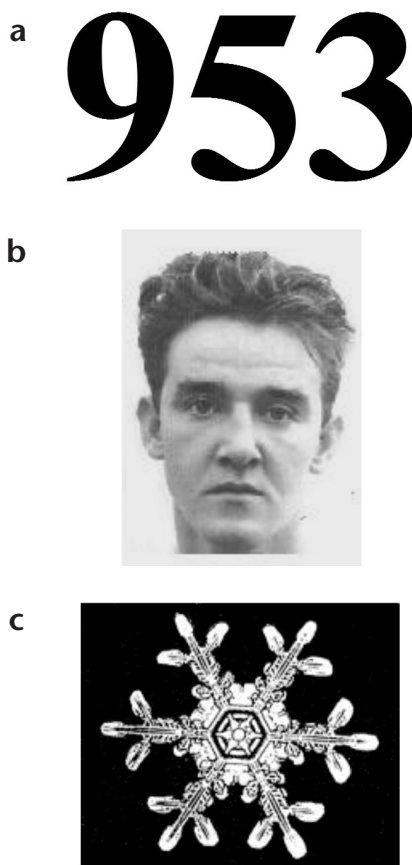
except during digit learning in the control subjects.

Our main interest was in the difference between the fMRI data of the SMs and control subjects (**Table 3**). The two groups were compared directly, and the resulting differences were of two sorts: (i) some brain areas, such as the right cerebellum, were active in both groups for all stimulus types but were more active in the SMs and (ii) more notably, some areas were active only in the SMs and not in the controls at the thresholds used. Several brain regions were active in SMs for all stimulus types, irrespective of performance: left medial superior parietal gyrus, bilateral retrosplenial cortex, and right posterior hippocampus. These findings are summarized in **Fig. 3** by showing the results of a conjunction analysis across the contrasts detailed in **Table 3**.

In addition to the above differences present for all stimulus types, areas more active in the SMs for digits were the right cingulate cortex, left fusiform cortex and left posterior inferior frontal sulcus. According to the probability map of this region[16], this activation is unlikely (probability 5–25%) to be in Broca's area (pars opercularis). For faces, the area that was more active in SMs was in the vicinity of right pallium; for snowflakes, the area in the vicinity of left pallium.

Had the memory performance of SMs and control subjects differed significantly across all tasks, it would be conceivable that the
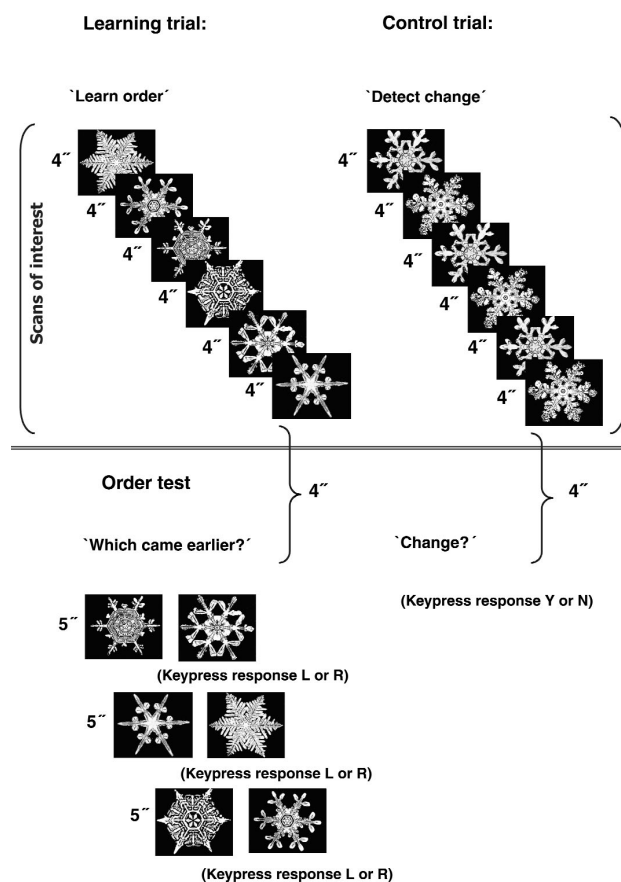
Learning trial: Control trial:

`Learn order´                      `Detect change´

Order test

`Which came earlier?´              `Change?´

(Keypress response Y or N)

(Keypress response L or R)

(Keypress response L or R)

(Keypress response L or R)

Fig. 2. Graphic representation of the structure of a sample learning and control trial during scanning (see Methods for details). Briefly, subjects learned sequences of items (in this example, snowflakes). They were tested after each sequence on their memory for the order of items (order test) and were also advised they would be tested after scanning for item recognition. For the non-learning control trials, two stimuli were alternated in presentation, and the task was to be alert to an obvious visual blurring of one of the pictures (this occurred very rarely and is not shown in this example).

fMRI activation differences detailed in **Table 3** and summarized in **Fig. 3** might merely reflect this difference in performance. However, our experimental design ensured a range of performance, from the SMs being much better than controls (digits) to both groups performing similarly (snowflakes). The main findings (**Fig. 3**) hold, irrespective of performance differences, showing that these regions were involved in the learning process *per se* and not merely in the efficacy of encoding. We did, however, also test for changes in activity associated with level of performance, and compared the SMs and control subjects directly. When performance scores were entered as covariates, the only difference to emerge between the groups was in the order test for digits, where bilateral ventral putamen was more active in the SMs (−21, −3, −3; 21, −3, −6).

DISCUSSION

We conclude that the increased activity in the medial parietal cortex, retrosplenial cortex and right posterior hippocampus of the SMs was not a function of better performance, as these differences pertained even when performance between the SMs and controls was matched, as in the snowflakes task. These brain regions are known to be important for memory, and are impli-

Table 3. Direct fMRI comparisons between the SMs and control subjects (where SMs > controls)[a]

Brain region	Digits	Faces	Snowflakes
	Talairach coordinates (*x, y, z*) of peaks		
Right posterior hippocampus	31, −32, −6	32, −26, −9	27, −30, −7
Left retrosplenial cortex	−12, −51, 18	−9, −60, 12	−9, −57, 9
Right retrosplenial cortex	15, −54, 18	15, −57, 12	21, −54, 9
Right cerebellum	18, −78, −36	21, −75, −39	21, −69, −30
Left medial superior parietal cortex	−9, −48, 57	−12, −75, 54	−3, −60, 60
Right cingulate cortex	18, −42, 42		
Left fusiform cortex	−42, −48, −21		
Left posterior inferior frontal sulcus	−42, 6, 27		
Vicinity of right pallidum		18, −6, −3	
Vicinity of left pallidum			−21, −9, 9

[a]There were no brain regions that were more active in control subjects, or regions only active in controls and not in SMs. There were no time × condition (stimulus type) interactions evident in either group.

cated in spatial memory and navigation[17–20]. Debriefing of subjects after scanning revealed that all of the SMs used mnemonics during the learning phase. Mnemonics are strategies for encoding information with the sole purpose of making it more memorable[21]. Nine out of the ten SMs used the mnemonic known as the 'method of loci' for some or all of the tasks. The origin of this ancient method, sometimes called the 'journey' or 'mental walk' technique[22], is attributed to the Greek poet Simonides of Ceos in 477 BC[1], who describes using routes and visualizing to-be-remembered items at salient points along the routes, and then mentally retracing those routes during recall. The efficacy of the method of loci is reflected in its continued use over two and a half millennia in virtually unchanged form. It is interesting to note that, although very proficient in the use of this spatial mnemonic, no structural brain changes were detected in the right posterior hippocampus of the SMs, as have been found in London taxi drivers[10]. This may be because taxi drivers store a large and complex spatial representation of London, whereas the SMs use and re-use a more constrained set of routes.

The distinctive activations of SMs may simply reflect differences between the two groups in the engagement of associative memory. However, debriefing of the subjects revealed striking similarities between the two groups in their use of feature selection and association. During the encoding of faces, both SMs and controls reported noting significant features (hair, eyes) or associating each face with a person they knew or with a personality trait. For the snowflakes, the main strategy for both groups was to select significant features and associate them with objects. Only the SMs associated the digit stimuli with images (in one case words and then images) of people, animals or objects. None of the control subjects reported such associations. In all cases, except the control subjects during digit learning, the left posterior inferior frontal sulcus, which is an area previously reported to be involved in learning associations, was active[23,24]. Direct com-
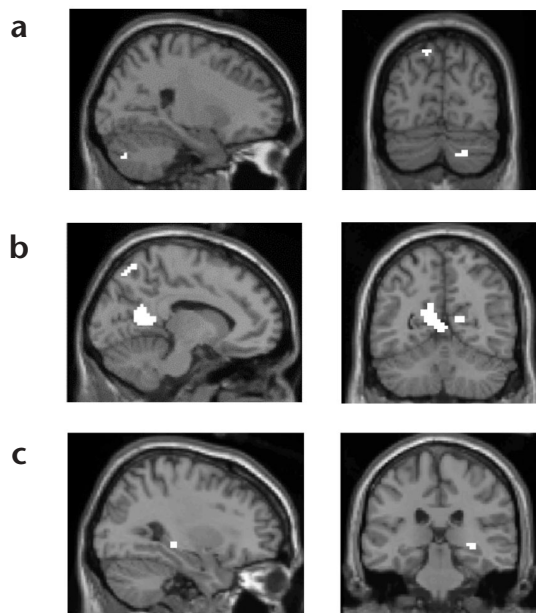
Fig. 3. Functional MRI results showing differences between the SMs and controls. Activations are shown on the Montreal Neurological Institute (MNI) structural MRI template. Activations are the result of a conjunction analysis of the contrasts presented in **Table 3**, and therefore show the group differences that were apparent for all stimulus types. (**a**) Areas more active for the SMs for all tasks: right cerebellum (18, −78, −39). (**b**) Areas active only in the SMs, commonly for all tasks: left medial superior parietal gyrus (−6, −69, 60), bilateral retrosplenial cortex (−12, −54, 18; 18, −57, 12) and (**c**) right posterior hippocampus (33, −33, −6).

parison between the two groups confirmed this area to be more active in SMs for digit learning (**Table 3**). Along with other activations such as those in the caudate nucleus[23], the posterior inferior frontal area may reflect the associative aspects of these learning tasks. Crucially, only the SMs proceeded to use their newly-associated stimuli in the route strategy. None of the control subjects reported using any standard mnemonic techniques.

We therefore believe that the parietal, retrosplenial and right posterior hippocampal activations in the SMs reflected the use of the route strategy, either in learning the new items on the routes and/or in retrieving the routes themselves, which were typically real and familiar. There are other possible interpretations; for example, the SMs were well-practiced in using mnemonics (on average, for more than eleven years; **Table 1**), and the observed pattern of activations may instead or in addition reflect the duration of use of the method of loci. Alternatively, it may be that the fMRI group differences relate to a special facility on the part of SMs for using this mnemonic. The examination of a control group of subjects newly instructed in the method of loci will be an important element of future studies to further clarify this issue.

Memory superiority has mainly been attributed to mnemonics[3,25]. Mnemonic devices are often regarded as overly complicated, requiring explicit effort to use, and thus limited in their relevance for everyday memory. In some situations, however, such devices are very effective, and it has been argued that mnemonics such as the method of loci do indeed organize information in a manner that is relevant our daily lives[21]. These strategies may simply be more efficient variations of normal memory functions[26], systematizing the natural process. Mnemonics are reported to be effective in memory remediation in elderly[27] and

special needs[28] populations. The value of mnemonics in the context of acquired brain injury and disease is less clear[29,30], although there is little knowledge of the precise brain areas engaged by different mnemonic strategies. The aim of the current study was not to examine mnemonics specifically or the method of loci, but rather to compare SMs and control subjects. Our findings do, however, indicate that fMRI could prove valuable in delineating the neural substrates of mnemonic techniques. This may extend the horizon for effective memory improvement in the general population and facilitate rational and focused rehabilitative interventions in patients.

In summary, we have addressed the long-standing question of why some people have superior memories compared with those of others. We found that those with superior memory use a spatial learning strategy and engage brain regions that are critical for spatial memory. The longevity and success of the method of loci in particular may point to a natural human proclivity to use spatial context—and its instantiation in the right hippocampus—as one of the most effective means to learn and recall information.

METHODS

Subjects. All participants gave informed written consent in accordance with the local research ethics committee. Data from 10 SMs are reported; all were male and one was left-handed (**Table 1**). Eight of the SMs are or have been placed at the highest levels in the World Memory Championships. All gave explicit consent for disclosure of this information. The remaining two SMs had both been studied previously, and their extraordinary memory feats are documented elsewhere[3]. Ten control subjects also participated. All were male, and each was matched with a SM according to age and handedness (**Table 1**). All participants were healthy at the time of scanning. For one SM, there was a query of dyslexia as a child in the early 1960s, but he has had no difficulties in adulthood; one was reported to have had seizures in childhood that resolved at puberty without recurrence.

Materials and procedure. During the fMRI scan, subjects were asked to learn items that were presented visually and to learn the order (sequence) in which they occurred. There were three types of stimuli: three-digit numbers, faces and snowflakes (**Fig. 1**). Different stimulus types were not mixed within a sequence. There were six items per sequence and five sequences of each stimulus type. The order of stimulus types was pseudorandom. Each item in a sequence was presented alone on the screen for 4 s (**Fig. 2**). After a sequence was presented, the subject then saw pairs of stimuli from that sequence and indicated by key press which of the two items came earlier in the sequence (note that the items could have been from any point in the sequence). There were three such pairs; thus subjects saw each item once more during this order recognition task. Each pair was on screen for 5 s, and the subject had to respond within this time. This retrieval task was included to provide an online assessment of order memory and to encourage subjects to actively engage in the learning tasks; although modeled, it was not the primary interest of the fMRI study.

There was a control task for each stimulus type. As in the learning tasks, stimuli appeared one at a time for 4 s each, but there were only two stimuli for control trials, and they were repeated alternately three times. Thus there was minimal memory load, and subjects paid attention for any change in the appearance of an item. In the case of the faces or snowflakes, this change was in the form of blurring of the image, and a change in the font used for the digits. The changes occurred only very rarely (once for each stimulus type in the scanning session). Subjects responded by key press to a visually presented question as to whether they had noted a change or not after the presentation of the control stimuli in a trial was complete. Thus, the learning and control tasks were comparable with respect to visual and perceptual inputs and (absence of) motor demands. All stimuli were presented on an off-white background and shown centrally.

After scanning, each subject performed forced-choice recognition memory tests for each stimulus type (outside of the scanner). Each test comprised items seen during scanning and an equal number of foils. The subject saw two items at a time on the screen for 4 s and responded by

key press to identify which one of each pair was seen during scanning. Subjects then indicated by key press whether or not they were confident in their response. Each subject was debriefed about how he had performed the tasks during scanning and the strategies, if any, he had used. In addition, a number of standard general abilities tests were also administered to assess whether SMs and control subjects were comparable in their basic intellectual, verbal and visual abilities.

Image acquisition and data analysis. Data were acquired using a 2-tesla Magnetom VISION (Siemens GmbH, Erlangen, Germany) MRI system. Contiguous multi-slice T2*-weighted fMRI images were obtained with echo-planar imaging (echo time (TE), 40 ms; whole head: 32 slices, each 3 mm thick, 3 s per volume). For each subject, high-resolution volumetric MR images were acquired using an optimized MPRAGE sequence affording enhanced gray/white matter contrast and segmentation[31]. Functional images were processed and analyzed using Statistical Parametric Mapping (SPM99, Wellcome Department of Imaging Neuroscience, London, UK) in a standard manner as described elsewhere[32], with a smoothing kernel of 8 mm full-width half maximum (FWHM).

The standard boxcar model was used to characterize fMRI activation effects. Each contrast (functional data for each stimulus minus those for its control task) was calculated for each subject and then brought to the second level in the standard manner using SPM99. The findings for each group (SMs and controls) were then calculated using a random effects analysis. Commonalities across all subjects were also calculated in a standard manner with SPM99, using contrasts from each subject. As these were all orthogonal, it was possible to ascertain which areas were commonly active across subjects for a given contrast. The main aim of the experiment was to consider any possible differences between SMs and control subjects. To examine this, the two groups were directly compared in SPM99 at the random effects level. Only those fMRI activations surviving a threshold of $P < 0.05$ corrected for multiple comparisons were considered; this applied throughout, for group effects, conjunction analyses and group differences. For two areas of particular interest specified in advance—the hippocampus and prefrontal cortex—we used a threshold of $P < 0.001$ uncorrected, although the majority of activations in these areas also survived the $P < 0.05$ corrected threshold.

Structural MRI data were analyzed using an optimized method of whole-brain voxel-based morphometry (VBM[12]) implemented in SPM99, using a smoothing kernel of 10 mm FWHM. Regionally specific differences in gray matter density between subject groups were assessed. The significance threshold was set at $P < 0.05$ (corrected).

Acknowledgments

Competing interests statement

The authors declare that they have no competing financial interests.

1. Yates, F.A. *The Art of Memory* (Pimlico, London, 1966).
2. Luria, A.R. *The Mind of a Mnemonist* (Penguin, Harmondsworth, UK, 1975).
3. Wilding, J. & Valentine, E. *Superior Memory* (Psychology Press, Hove, UK, 1997).
4. Brown, E. & Deffenbacher, K. Forgotten mnemonists. *J. Hist. Behav. Sci.* **11**, 342–349 (1975).
5. Neisser, U. *Memory Observed: Remembering in Natural Contexts* 377–381 (Freeman, San Francisco, 1982).
6. Amidzic, O., Riehle, H.J., Fehr, T., Wienbruch, C. & Elbert, T. Pattern of focal γ-bursts in chess players. *Nature* **412**, 603 (2001).
7. Presenti, M. *et al.* Mental calculation in a prodigy is sustained by right prefrontal and medial temporal areas. *Nat. Neurosci.* **4**, 103–107 (2001).
8. Gauthier, I., Skudlarski, P., Gore, J.C. & Anderson, A.W. Expertise for cars and birds recruits brain areas involved in face recognition. *Nat. Neurosci.* **3**, 191–197 (2000).
9. Butcher, J. Dominic O'Brien—master mnemonist. *The Lancet* **356**, 836 (2000).
10. Maguire, E.A. *et al.* Navigation-related structural change in the hippocampi of taxi drivers. *Proc. Natl. Acad. Sci. USA* **97**, 4398–4403 (2000).
11. Schlaug, G., Jancke, L., Huang, Y. & Steinmetz, H. *In vivo* evidence of structural brain asymmetry in musicians. *Science* **267**, 699–701 (1995).
12. Ashburner, J. & Friston, K.J. Voxel-based morphometry—the methods. *Neuroimage* **11**, 805–821 (2000).
13. Gadian, D.G. *et al.* Developmental amnesia associated with early hypoxic-ischemic injury. *Brain* **123**, 499–507 (2000).
14. Good, C.D. *et al.* Cerebral asymmetry and the effects of sex and handedness on brain structure: a voxel based morphometric analysis of 465 normal adult human brains. *Neuroimage* **14**, 685–700 (2001).
15. Bentley, W.A. & Humphreys, W.J. *Snow Crystals* (Dover, New York, 1962).
16. Tomaiuolo, F. *et al.* Morphology, morphometry and probability mapping of the pars opercularis of the inferior frontal gyrus: an *in vivo* MRI analysis. *Eur. J. Neurosci.* **11**, 3033–3046 (1999).
17. Maguire, E.A. *et al.* Knowing where, and getting there: a human navigation network. *Science* **280**, 921–924 (1998).
18. Burgess, N., Maguire, E.A. & O'Keefe, J. The human hippocampus and spatial and episodic memory. *Neuron* **35**, 625–641 (2002).
19. O'Keefe, J. & Nadel, L. *The Hippocampus as a Cognitive Map* (Oxford Univ. Press, Oxford, 1978).
20. Maguire, E.A. The retrosplenial contribution to human navigation: a review of lesion and neuroimaging findings. *Scand. J. Psychol.* **42**, 225–238 (2001).
21. Bellezza, F.S. Mnemonic devices: classification, characteristics and criteria. *Rev. Educ. Res.* **51**, 247–275 (1981).
22. Bower, G.H. Analysis of a mnemonic device. *Am. Scientist* **58**, 496–510 (1970).
23. Toni, I. & Passingham, R.E. Prefrontal-basal ganglia pathways are involved in the learning of arbitrary visuomotor associations: a PET study. *Exp. Brain Res.* **127**, 19–32 (1999).
24. Dolan, R.J. & Fletcher, P.C. Dissociating prefrontal and hippocampal function in episodic memory encoding. *Nature* **388**, 582–585 (1997).
25. Chase, W.G. & Ericsson, K.A. Skill and working memory. in *The Psychology of Learning and Motivation* Vol. 16 (ed. Bower, G.H.) 1–58 (Academic, New York, 1982).
26. Roediger, H.L. The effectiveness of four mnemonics in ordering recall. *J. Exp. Psych. Hum. Learn. Mem.* **6**, 558–567 (1980).
27. Verhaeghen, P. & Marcoen, A. On the mechanisms of plasticity in young and older adults after instruction in the method of loci: evidence for an amplification model. *Psychol. Aging* **11**, 164–178 (1996).
28. Bender, B.G. & Levin, J.R. Pictures, imagery, and retarded children's prose learning. *J. Educ. Psych.* **70**, 583–588 (1978).
29. Richardson, J.T.E. The efficacy of imagery mnemonics in memory remediation. *Neuropsychologia* **33**, 1345–1357 (1995).
30. Wilson, B.A. Memory rehabilitation. in *Neuropsychology of Memory* 3rd edn. (eds. Squire, L.R. & Schacter, D.L.) 263–272 (Guilford Press, New York, 2002).
31. Deichmann, R., Good, C.D., Josephs, O., Ashburner, J. & Turner, R. Optimization of 3D MP-RAGE sequences for structural brain imaging. *Neuroimage* **12**, 112–127 (2000).
32. Maguire, E.A., Vargha-Khadem, F. & Mishkin, M. The effects of bilateral hippocampal damage on fMRI regional activations and interactions during memory retrieval. *Brain* **124**, 1156–1170 (2001).
33. Oldfield, R.C. The assessment and analysis of handedness: the Edinburgh Inventory. *Neuropsychologia* **9**, 97–113 (1971).
34. Nelson, H.E. & Wilson, J.R. *National Adult Reading Test* (NART) 2nd edn. (Berkshire, Windsor, UK, 1991).
35. *Wechsler Abbreviated Scale of Intelligence* (WASI). (The Psychological Corporation, San Antonio, Texas, 1999).
36. Rey, A. L'examen psychologique dans les cas d'encephalopathy. *Archives de Psychologie* **28**, 286–340 (1942).
37. Osterrieth, P.A. Le test de copie d'une figure complexe. *Archives de Psychologie* **30**, 206–356 (1944).
38. Coughlan, A. & Hollows, S.E. *Adult Memory and Information Processing Battery* (AMIPB). Psychology Department, St. James Hospital, Leeds, UK (1985).
39. *Wechsler Adult Intelligence Scale – Revised* (British Adaptation) (WAIS-R). (The Psychological Corporation, San Antonio, Texas, 1986).
40. Bennett-Levy, J., Polkey, C.E. & Powell, G. Self-report of memory skills after temporal lobectomy: the effect of clinical variables. *Cortex* **16**, 543–557 (1980).
41. McMillan, T.M. Investigation of everyday memory in normal subjects using the Subjective Memory Questionnaire (SMQ). *Cortex* **20**, 333–347 (1984).