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# Cambridge Neuropsychological Test Automated Battery (CANTAB): A Factor Analytic Study of a Large Sample of Normal Elderly Volunteers

**Abstract**

The CANTAB battery was administered to a large group (n = 787) of elderly volunteers in the age range from 55 to 80 years. This battery, which is based on tests used to identify the neural substrates of learning and memory in non-human primates, has now been extensively used in the assessment of various forms of dementia and also validated on patients with neurosurgical lesions of the frontal and temporal lobes. The tests employed were pattern and spatial recognition, simultaneous and delayed matching to sample, learning of visuo-spatial paired associates, a matching to sample, reaction time task and a test of spatial working memory. The sample was banded into different IQ bands based on performance on 5 standard tests of intelligence. The MMSE was also administered to exclude cases of possible dementia (n = 16) in the normal sample. In general, performance declined with age and IQ, but these factors did not interact. A factor analysis (with varimax rotation) identified 4 factors with eigenvalues greater than 1, which accounted for over 60% of the variance. Factor 1 was equated with general learning and memory ability and loaded significantly with the Intelligence scores; factor 2 was related to speed of responding and loaded most heavily with Age. Comparisons were also made of performance on CANTAB of those subjects with dementing scores on the MMSE and the lowest 5th percentile of the population sample. The results are discussed in terms of the utility of the CANTAB battery for the assessment of dementia and of the implications for theories of changes in cognitive function during normal aging.

**Key Words**
Memory
Attention
Cognition
Cognitive test battery
MMSE
Aging
Alzheimer's disease
Parkinson's disease
Factor analysis
CANTAB

## Introduction

In recent years, methods of testing cognitive function in elderly and dementing patients have been augmented by batteries of computerised tests [1–3]. New technology, such as the use of touch-sensitive screens rather than keyboards, have been used to make these accessible, even to the frail and confused elderly. This allows the many other advantages of computerised testing to be realised: computerised tests can immediately check the accuracy of each response made and so provide patients with instant feedback; they can continuously check to ensure that task demands are correctly understood and can continuously adjust levels of difficulty to challenge, but not to embar-

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rass them; from any task it is possible to derive, record and automatically analyse several different performance indices, rather than merely one. Direct feedback and appropriately graduated levels of challenge have been shown to increase interest in tasks and so promote motivation to do well. This mitigates the perennial problem in assessing elderly patients that not only the limits to their abilities but also their levels of motivation may be reduced by age or pathology. Computerised tests offer neutral settings and highly consistent modes of presentation that reduce the large experimenter effects that often reduce the validity of assessments. All of these factors obviously improve the reliability and comparability of results across studies.

Cambridge Automated Neuropsychological Test Battery (CANTAB) was designed to exploit these advantages [4–7]. The original theoretical impetus was to adapt paradigms developed for testing animal models of dementia in order to relate the findings to man. To do this it was necessary to find ways of varying task demands appropriately to a very wide spectrum of ability. However, as the battery was developed, tests based on methodological advances in neuropsychological assessments of human patients were also added: for example the Visual Memory section of the battery originally consisted of tests of pattern and spatial serial recognition memory, and a delayed matching to sample (DMTS) procedure analogous to those used by Gaffan [8] and Mishkin [9] and their colleagues to determine the neural basis of visual recognition memory in infrahuman primates [see also 10]. Based on the delayed-(non)-matching-to-sample paradigm, Mishkin [9] has proposed a neural model of visual recognition memory that includes as important elements, structures of the temporal lobe, including the hippocampus. To these tests have been added a more complex visuospatial paired associated task in which subjects have to learn the spatial locations of different patterns, analogous to conditional associative learning paradigms used by Petrides [11] to test both monkeys and human patients with temporal, but also frontal lobe damage. Finally, in this battery we have employed a test based somewhat on the 8 arm radial maze test to assess 'working memory' in rodents [12], but more particularly in non-human primates receiving circumscribed lesions of the prefrontal cortex [13]. We have already shown that performance on this test is impaired in patients with neurosurgical lesions of the frontal cortex [7].

Because many of these tests make demands on perceptual information processing, on attentional resources and on central executive function, it is important to design memory tests which control for these factors and so can reveal independent, residual changes in memory function. For example, in the DMTS test in the CANTAB battery the contribution of attentional changes to task performance is assessed by including a simultaneous matching to sample task. Similarly, possible contributions of changes in information processing load have been taken into consideration by measuring reaction times to match remembered stimuli to presented samples and by systematically varying task difficulty by increasing the sizes of the sets of distractors among which target stimuli are embedded. Executive function, which determines the strategies that subjects may adopt in particular memory tasks, is assessed independently of these tasks by inclusion of a spatial working memory task in which subjects have to develop and use their own strategies to search through a set of spatial locations.

The CANTAB batteries have been extensively used to assess cognitive performance in a number of neuropsychiatric disorders including dementia of the Alzheimer [5, 14–16], Lewy body [17, 18] and frontal [19] types, Korsakoff's syndrome [20], depression in the elderly [21], basal ganglia disorders such as Parkinson's disease [5, 6, 20, 22–24], progressive supranuclear palsy [25] and multiple system atrophy [26]. The validity of the tests in distinguishing between neurosurgical populations with localised excisions of the frontal or temporal lobes has also been demonstrated [7, 27, 28].

In all these studies it has been possible to compare patients individually to appropriately matched normal controls. This has been satisfactory for the comparisons intended but has not allowed us to determine the general background effects of individual differences in factors such as age, gender and intelligence independently of the pathology examined. It is of obvious practical importance to obtain baseline data on large groups of normal individuals in a wide range of older age groups against which the performance of various groups of patients can be assessed.

The lack of such data is also a restriction to development of theories of individual differences. A lively research topic in current cognitive psychology and gerontology is the extent to which the cognitive concomitants of individual differences in age, or in general intelligence can be accounted for in terms of changes or individual differences in the efficiency of particular brain structures [29, 30]. For these reasons we administered the CANTAB battery to a group of 787 normal elderly volunteers who had all been repeatedly assessed, over a period of 7 years, on two other, different batteries of cognitive tasks. These

**Table 1.** Characteristics of population by age

| Age group | n | Mean age | Mean NART | Mean INTEL |
|---|---|---|---|---|
| 55–59 | 79 | 57.7 (1.2) | 118.6 (6.6) | +0.28 |
| Male | 10 | 57.2 (0.9) | 118.4 (8.6) | +0.47 |
| Female | 69 | 57.8 (1.3) | 118.6 (6.4) | +0.25 |
| 60–64 | 123 | 62.3 (1.4) | 118.0 (6.5) | +0.19 |
| Male | 20 | 61.9 (1.3) | 119.6 (6.0) | +0.47 |
| Female | 103 | 62.4 (1.4) | 117.7 (6.6) | +0.14 |
| 65–69 | 222 | 67.3 (1.4) | 117.9 (6.0) | +0.04 |
| Male | 56 | 67.2 (1.5) | 119.3 (6.0) | +0.33 |
| Female | 166 | 67.3 (1.4) | 117.5 (5.9) | -0.05 |
| 70–74 | 219 | 72.0 (1.5) | 117.8 (6.0) | -0.04 |
| Male | 65 | 72.3 (1.4) | 118.0 (6.1) | +0.18 |
| Female | 154 | 71.8 (1.5) | 117.7 (6.0) | -0.13 |
| 75–79 | 128 | 76.6 (1.4) | 116.2 (6.3) | -0.22 |
| Male | 40 | 76.4 (1.5) | 117.7 (5.4) | +0.17 |
| Female | 88 | 76.7 (1.4) | 115.6 (6.6) | -0.39 |

NART = National Adult Reading Test; INTEL = mean weighted z score of the intelligence tests administered (minus scores, low; positive scores, high IQ); standard deviations in parentheses.

**Table 2.** Characteristics of population by IQ band

| IQ Band | n | Mean age | Mean NART | Mean INTEL |
|---|---|---|---|---|
| IQ1 | 224 | 69.2 (5.7) | 111.0 (5.6) | -0.97 |
| Male | 38 | 69.3 (4.9) | 110.3 (5.2) | -0.87 |
| Female | 186 | 69.1 (5.8) | 111.2 (5.7) | -0.99 |
| IQ2 | 235 | 69.1 (5.9) | 117.5 (3.7) | -0.10 |
| Male | 60 | 71.5 (5.4) | 117.0 (4.0) | -0.03 |
| Female | 175 | 68.3 (5.8) | 117.7 (3.70) | -0.12 |
| IQ3 | 312 | 67.3 (5.9) | 122.5 (2.7) | +0.83 |
| Male | 93 | 68.9 (5.6) | 122.8 (2.7) | +0.91 |
| Female | 219 | 66.6 (6.0) | 122.5 (2.7) | +0.79 |

NART = National Adult Reading Test; INTEL = mean weighted z score of the intelligence tests administered (minus scores, low; positive scores, high IQ); standard deviations in parentheses.

additional data allowed us to extend our analyses to evaluate variations in CANTAB scores with individual differences in age between 55 and 80, and in performance on five different measures of general intelligence, in the context of variations in scores on a variety of other measures of cognitive ability.

## Method

*Subjects.* Subjects were 787 normal healthy residents of Newcastle-upon-Tyne aged from 55 to 80 years. These had volunteered to take part in a large scale longitudinal study of the cognitive effects of normal ageing funded by the Medical Research Council and the Economic and Research Councils and carried out at the University of Newcastle-upon-Tyne. Over a 7-year period prior to this study all had been repeatedly assessed on three different IQ tests: National Adult Reading Test, NART [31], Mill Hill Vocabulary Test, 'A' and 'B' [32], and AH41 and AH42 [33]. This allowed the subject population to be divided orthogonally, for purposes of data analysis, into 5 different age groups (table 1) and 3 different IQ test score groups (table 2) in terms of their attainment on the several different IQ measures. For the purpose of obtaining a single IQ measure, we transformed all IQ test scores to z-scores and the resulting measure, 'INTEL' is the average of these scores and is summarized in table 2. The highest IQ band group is called IQ3, the middle group, IQ2 and the lowest group, IQ1.

To detect and independently study any individuals who might be at risk of dementia all volunteers were also screened on the Mini Mental State Examination (MMSE) [34]. All volunteers were then tested on all the subtests of the CANTAB battery as described below. The main analysis of results was carried out on the 771 individuals who attained MMSE scores greater than 23. Data for the 16 individuals with MMSE scores less than 24 are presented separately.

*Equipment and Procedure*

The main tests were taken from the CANTAB. These were a series of computerised tasks run on a Acorn BBC Master 128 microcomputer with a resolution Microvitec 12-inch VDU and a Microvitec Touchtec 501 touch-sensitive screen. On one of the tests (matching-to-sample – visual search – task), subjects were trained to depress a large key-pad interfaced into the serial port of the microcomputer with their hand for the purpose of measuring reaction times. Subjects sat at a comfortable height approximately 0.5 m from the monitor. It was explained that they would have to respond to stimuli by touching the screen. They were introduced to the apparatus by way of a task which screened them for possible difficulties in motor ability that might affect their performance. In this 'motor screening task' they were asked to respond to a series of flashing crosses on the screen by placing the index finger of their preferred hand on the centre point of each cross as soon as possible after it appeared. Once each cross had been accurately touched the next cross appeared after a 6-second delay. Following a short demonstration by the experimenter, in which three consecutive crosses were touched, subjects were presented with a series of ten crosses to touch. All volunteers passed this introductory screening task and were then given the following tests in the order described.

*Pattern Recognition.* This test was presented in two phases. Subjects were first shown a series of 12 coloured patterns (set 1) which appeared one at a time, for 3 s, inside a white box located in the centre of the screen. After each pattern the screen was cleared and the next appeared. In the second (recognition) phase, 12 pairs of coloured patterns appeared successively, and one at a time. One member of each pair was a pattern that had appeared in set one (target pattern) and the other was a novel pattern. During the recognition phase the target patterns appeared in the reverse order of their original presentation and the distractor patterns differed in form but not in colour from members of the target set. Subjects responded to each pair by touching the pattern they recognised as having been a member of the target set. The programme signalled satisfactory registration of each response by sounding a tone. Visual feedback of accuracy of each response was automatically provided by appearance of a green tick or red cross. This cycle was then repeated with 12 new patterns (set 2) and the subject's total score (maximum possible = 24) was expressed as the percentage of correct to total responses made.

*Spatial Recognition.* In the initial (presentation) phase a series of 5 unfilled 1-inch white squares appeared for 3 s, one at a time, each at a different spatial location on the screen. In the second (recognition) phase, two squares appeared simultaneously. One, the target, occupied a location used during the presentation phase. The other, the distractor, appeared in a previously unused location. The subject had to recognise and tap the target. During the recognition phase the targets appeared in the reverse order in which they had appeared during presentation. The programme signalled that it had registered each response by a tone, and provided visual feedback of accuracy by green ticks and red crosses. This procedure was then repeated 3 more times, using new target and distractor locations on each occasion. The subject's score was expressed as the percentage correct of total responses made (i.e. 20).

*Simultaneous and Delayed Matching to Sample.* At the beginning of each trial, a complex abstract pattern consisting of four quadrants, each differing in colour and form, appeared in the centre of the screen for a period of 4.5 s. Subjects were told to study the pattern, since they would later be required to identify it among three 'distractor' patterns. In the *simultaneous* condition, 4 choice patterns then appeared, located under the sample pattern. The subject was required to respond by touching the choice pattern that exactly matched the sample pattern in both colour and shape. On each display only one of the choice patterns matched the sample. One of the other choice patterns was a novel distractor, differing from the sample in both colour and shape. One had the same colours as the sample but the same shape as the novel distractor while the other had the same shape as the sample but the same colours as the novel distractor. To discourage mnemonic strategies based on remembering the colour and shape of a single quadrant, each of the 4 choice patterns had one, randomly chosen quadrant in common [fig. 1 of ref. 24]. Registration of each response was signalled by an auditory tone and green ticks and red crosses provided visual feedback of accuracy. After an incorrect response subjects had to continue to choose until they touched the correct target stimulus. The interval between the appearance of the 4 choice patterns and the subject's response (reaction time), whether correct or incorrect, was timed in centiseconds.

The *delay* condition was identical to the *simultaneous* condition except that the sample pattern disappeared from the screen immediately after the initial 4.5-second study period. A 0-, 4- or 12-second delay then followed before the display of 4 choice patterns appeared and subjects were required to make their selection. Following three practice trials (one each of simultaneous, 0 and 12 s), there were a total of 10 test trials on each of the four simultaneous and delay conditions presented sequentially, and in a pseudo random order (total test trials = 40).

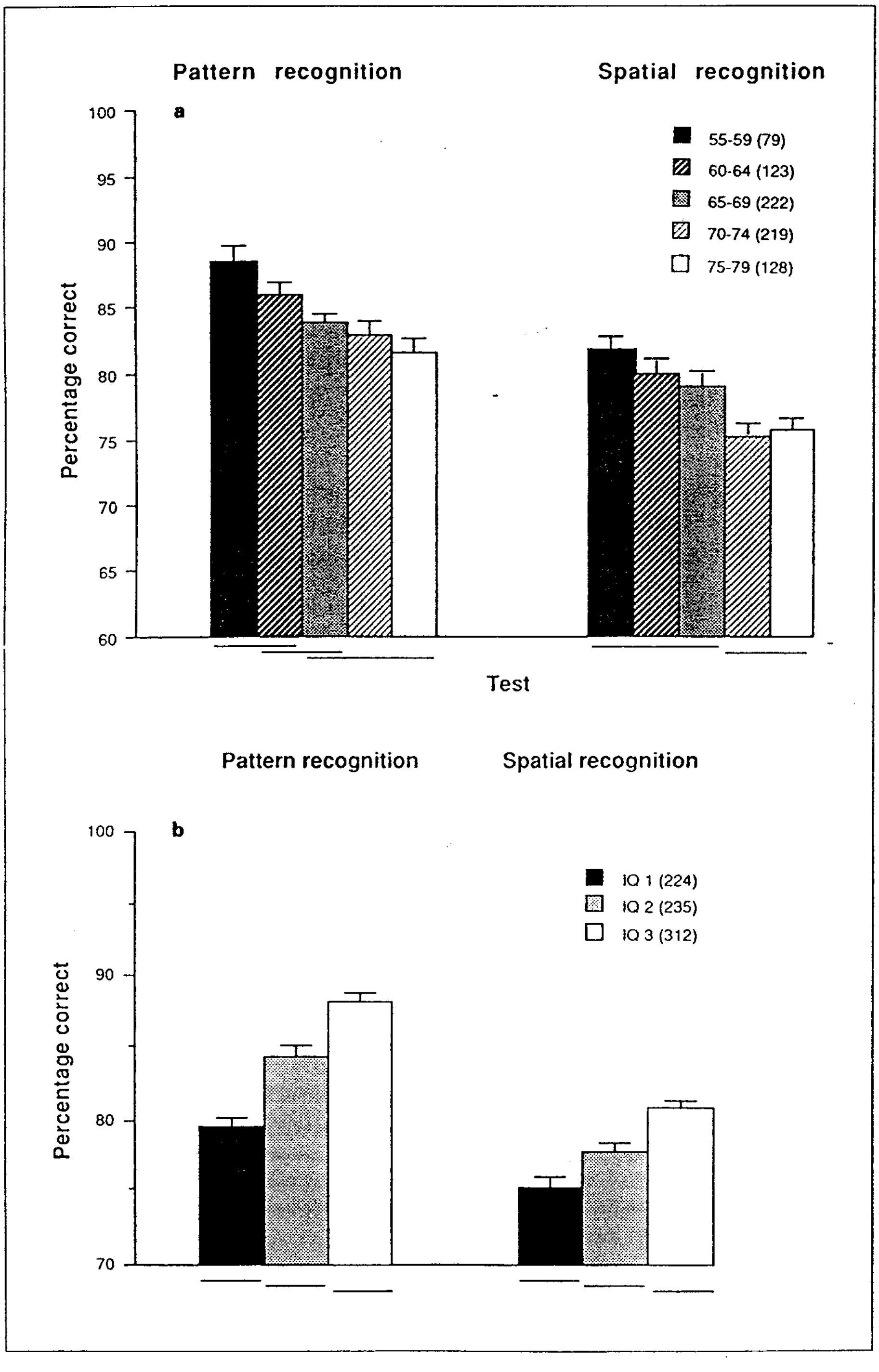
In each of the simultaneous and delay conditions, the score was the number of correct recognitions made on the first choice in each of the simultaneous and delay conditions. Errors in each of the four test conditions were also analysed to determine which of the three types of distractors had been incorrectly chosen (shape, colour or unrelated). Finally, in each condition, mean RTs were computed for those trials in which the first choice had been correct.

*Visuospatial Paired Associates Learning.* In this test, subjects were required to remember up to 8 pattern-location associations. Initially, 6 solid white boxes were presented around the screen [fig. 1 of ref. 24] and subjects were told that these would 'open up' in turn, showing them what was inside. Their task was to look for coloured patterns in the boxes and to remember which pattern belonged in which box. Each box opened for 3 s and closed again before the next box opened, one by one in a randomized sequence. On the first trial, only one of the boxes contained a coloured pattern. Immediately after the last box had opened this pattern was presented in the centre of the screen and the subject was required to respond by touching the box in which it had appeared. Feedback was *not* provided after each response although, if all choices had been correct, the words 'all correct' appeared in the centre of the screen and the subject proceeded to the next trial. If the choice had been incorrect, the boxes were successively reopened and shut for 2 s each (*reminding* phase). The subject was then given a second attempt to correctly locate the pattern. On each trial, subjects were allowed up to nine *reminding* phases, making ten attempts in all. If they failed all of these, the series of tests was stopped at this point and the conditions experienced were scored as described below. As soon as any of these nine possible further attempts had been successful the test moved forward to the next stage. After the initial stage with one pattern, there was one further stage with a single pattern, then two stages with two patterns each, two stages with three patterns each and then one stage with six patterns (i.e. one in every box). Finally, two extra boxes were added to the array on the screen and the subject was required to correctly locate a total of eight patterns. Subjects automatically moved from one stage to the next by correctly locating all of the patterns, either after the initial *presentation* phase or after one of the nine *reminding* phases.

Performance was scored using three indices: (1) *Trials;* the total number of presentations required (maximum score = 10 presentations per trial) to correctly locate all of the patterns summed across each of the eight stages. Subjects were assigned the maximum score of 10 for stages not attempted due to failure at an earlier stage. (2) *Errors;* the total number of errors (incorrect placements) summed across the eight stages. (3) The *First trial correct memory* score was the total number of patterns correctly located after the first presentation, summed across the eight stages (range = 0–26).

*Spatial Working Memory.* Subjects were required to 'search through' a number of boxes presented on the screen in order to collect 'blue tokens' hidden inside [fig. 1 of ref. 23]. On any one display presentation a single token would be 'hidden' inside one of the boxes and subjects were to search, by touching and 'opening' boxes in turn, until they found it. At this point the next token would be hidden. Once a blue token had been found within a particular box, that box would never again be used to hide a new token. Errors were scored according to the number of occasions on which a subject returned to open a box in which they had already found a blue counter during a previous search. The performance index analysed was the total number of those errors summed over twelve trials on this task (4 each with 4, 6 and 8 boxes).

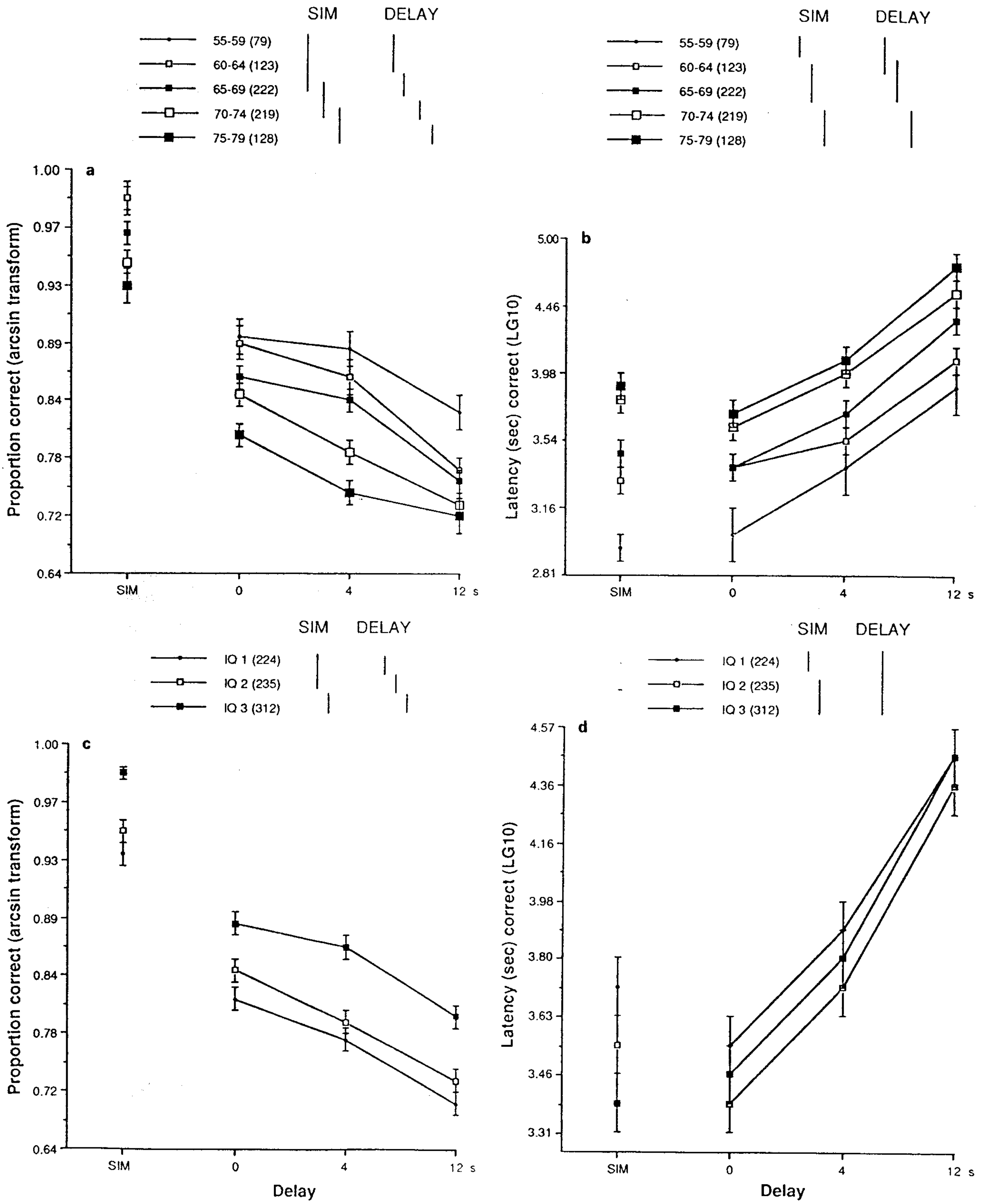
*Matching to Sample (Visual Search for Designated Targets).* A central red box surrounded by eight white boxes appeared on the screen. To initiate each trial, the subject was required to hold down a key pad which required minimal pressure. Once the subject depressed the key pad the boxes opened to reveal the central target stimulus surrounded by the choice stimuli among which an identical match had to be located. To begin with the subject was shown the arrangement and told to release the key pad as fast as possible and touch the identical stimulus in the peripheral boxes to the central sample stimulus. Feedback was provided on the screen for correct and incorrect responses. On an equal proportion of trials there was 1, 2, 4 or 8 different patterns to choose from. There were 4 examples of increasing set size, before beginning the 48 test trials. The test stimuli resembled those used in the delayed matching to sample test. Each of the test stimuli was made up of 4 quadrants which varied according to colour and pattern, but the same 4 colours were used for a given set of choices. For set sizes greater than 1, half of the stimuli were derived from the target stimulus and half from the distractor stimulus, by varying the relative positions of the quadrants [see fig. 2 of ref. 6].




1

**Fig. 1.** Pattern and spatial recognition memory accuracy performance as a function of age (**a**) and intelligence score (**b**). Values are given as means + SEM. The lines beneath the histograms summarise the results of the post hoc tests following analysis of variance. Groups with overlapping lines do not differ significantly from one another; those groups not sharing an overlapping line are significantly different.

**Fig. 2.** Simultaneous and delayed matching to sample performance. Accuracy and latency measures as a function of age (**a, b**); as a function of intelligence score (**c, d**). Both the accuracy scores and latency scores were transformed prior to statistical analysis and these variables are plotted on the appropriate scale. Other conventions as in figure 1.


SIM
DELAY
55-59 (79)
60-64 (123)
65-69 (222)
70-74 (219)
75-79 (128)
a
Proportion correct (arcsin transform)
1.00
0.97
0.93
0.89
0.84
0.78
0.72
0.64
SIM
0
4
12 s
b
Latency (sec) correct (LG10)
5.00
4.46
3.98
3.54
3.16
2.81
IQ 1 (224)
IQ 2 (235)
IQ 3 (312)
c
d
4.57
4.36
4.16
3.98
3.80
3.63
3.46
3.31
Delay

2

**Table 3.** Two-way ANOVA: summary

| | Age banding $F_{4,698}$ | Intelligence banding $F_{2,698}$ | A × I $F_{8,698}$ |
|---|---|---|---|
| Pattern recognition | 3.96 | 36.05 | 1.70 |
| Spatial recognition | 5.95 | 12.49 | 0.57 |
| Simultaneous MTS | 3.90 | 8.40 | 0.17 |
| Paired associates | | | |
| Total trials | 15.08 | 12.86 | 1.09 |
| Total errors | 14.40 | 10.67 | 0.85 |
| Memory score | 13.68 | 12.40 | 1.33 |
| Spatial working memory | 13.44 | 24.70 | 0.91 |

**Table 4.** Three-way analyses of variance for DMTS: summary

| | Accuracy | | Latency | |
|---|---|---|---|---|
| | F | d.f. | F | d.f. |
| Age | 13.35 | 4, 756 | 7.92 | 4, 717 |
| Intelligence | 35.22 | 2, 756 | 1.46 | 2, 717 |
| Delay | 82.00 | 2, 1512 | 275.59 | 2, 1434 |
| A × I | 1.23 | 8, 756 | 0.63 | 8, 717 |
| A × D | 1.86 | 8, 1512 | 0.87 | 8, 1434 |
| I × D | 1.44 | 4, 1512 | 1.83 | 4, 1434 |
| A × I × D | 1.00 | 16, 1512 | 0.73 | 16, 1434 |

## Results

The profile of performance as a function of age and IQ group is illustrated for each test with figures summarising differences between age and intelligence groups and tables 3 and 4 summarising the main effects and interactions found in analyses of variance (ANOVAs).

*Pattern and Spatial Recognition*

Accuracy of performance declined with age on both the pattern and spatial recognition tasks as shown in figure 1a although at slightly different rates as evidenced from the post hoc comparisons made between each age group, depicted in the figure. Scores declined smoothly and systematically from high to low IQ groups (fig. 1b).

Separate analyses of the effects of Gender (covarying for both age and intelligence score) found no difference between men and women for pattern recognition ($F_{1,709}$ = 1.81, $p > 0.05$), but a small significant male advantage for spatial recognition ($F_{1,709}$ = 4.18, $p < 0.05$) (mean scores; males 79.55%: females 77.65%).

*Simultaneous and Delayed Matching to Sample*

Accuracy on the simultaneous matching condition declined significantly with age (fig. 2a). However it is important to stress that overall levels of performance were excellent, and that even the oldest age group attained 93% accuracy. Latency scores show a markedly different pattern (fig. 2b). While the youngest subjects were no more accurate than the 60- to 64-year-olds, they were significantly faster. Moreover, although the two oldest age groups (70–74 and 75–79) were equivalently fast, the 75- to 79-year-olds were significantly less accurate. These contrasts imply differences in speed/error trade-off functions with age. There was a significant effect of intelligence band for both accuracy and latency (table 3, fig. 2a,b). For both measures, the high IQ group (IQ3) performed significantly better than either the middle (IQ2) or the low (IQ1) groups, who did not differ. An analysis of gender effects, covarying for both age and IQ test score, found that female subjects were slightly, but significantly faster at simultaneous matching to sample ($F_{1,709}$ = 4.18, $p < 0.05$).

In the delayed matching to sample condition, as expected, performance declined as a function of delay duration. Although overall accuracy did decline with increasing age, there was no significant difference in the rate of decline in accuracy with increasing delay intervals as a function of age (table 4). However the delay × age group interaction approached significance ($p = 0.064$) and so it was thought appropriate to consider the simple main effects of age group as function of delay. Inspection of figure 2a shows that performance of the two youngest age groups is indistinguishable except at the longest (12 s) delay. In contrast, for the two oldest age bands, a significant difference was found at short delays, but not at the longest delay. Counts of the different kinds of errors made found that in 74% of cases the distractor was of the same colour but different shape, in 21.5% of cases the distractor was of the same shape but different colour, and in 4.5% of cases the random distractor was chosen in error. Overall, it seems that there is some evidence to support the hypothesis that short-term forgetting rate increases with age and that, possibly because of encoding strategies that the subjects used, some stimulus aspects are less well encoded, or more rapidly forgotten than others.

Latencies showed a similar pattern of effects. Latency increased as a function of delay interval indicating that, like accuracy, it is a good index of efficiency of short-term retention. However, unlike the findings for accuracy, the age × delay interaction fell far short of significance. Figure 2b illustrates this, showing that all age groups showed

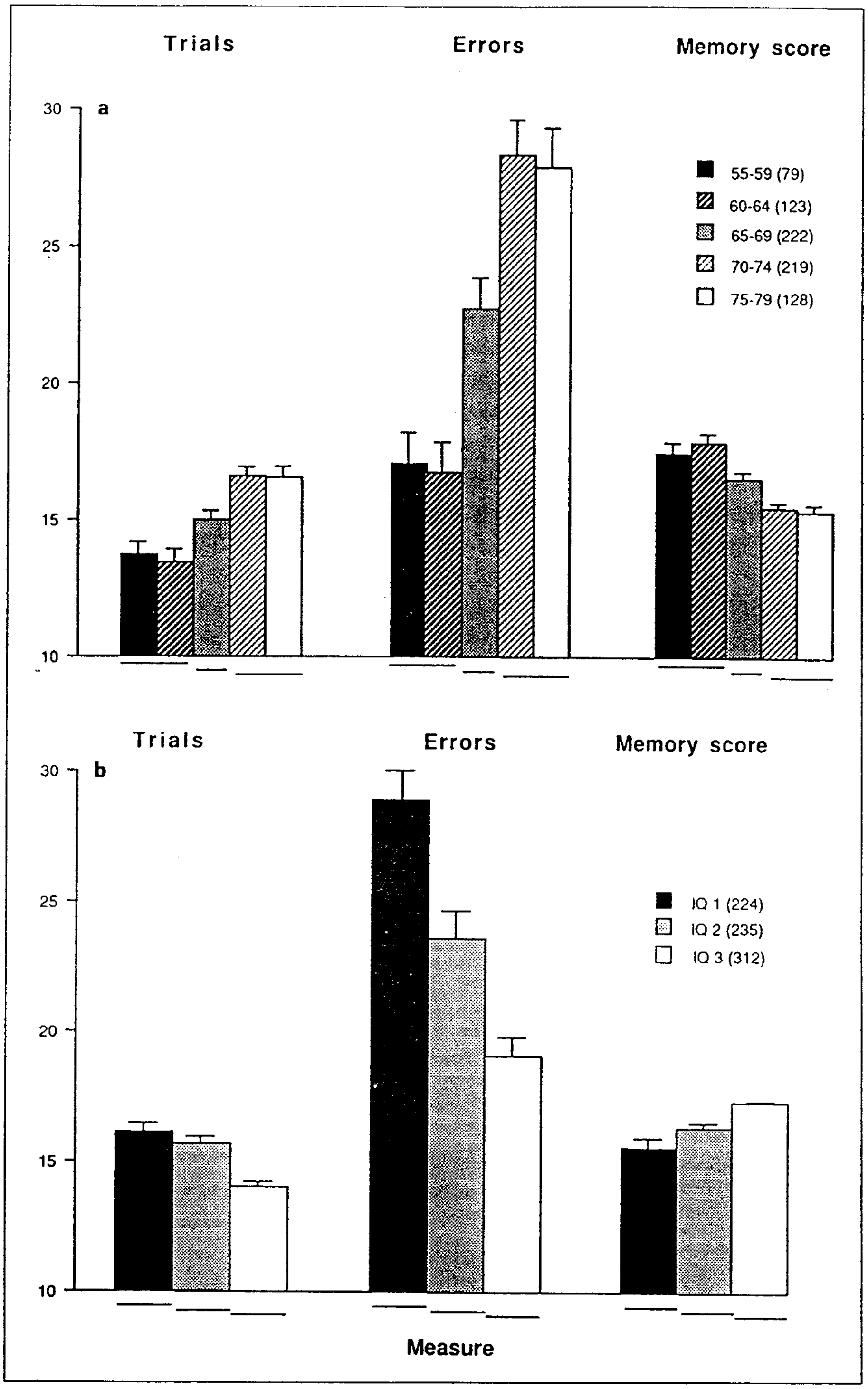



**Fig. 3.** Visuospatial paired associates. Summaries of the 3 main measures of performance (mean + SEM scores) plotted for age (**a**) and intelligence score (**b**) groups. Other conventions as in figure 1.

similar increases in latency with increasing delay. The single exception is that the 60- to 64-year band are disproportionately slow at the 0-second delay. Since these subjects made few errors at this delay interval, this perhaps represents a sacrifice of latency to increase accuracy.

Differences in short-term memory performance between IQ groups were much less clear-cut. The IQ3 group was significantly more accurate than either IQ2 or IQ1 groups at all delay intervals, but latencies did not differ significantly across the groups from 0 to 12 s (fig. 2c, d).

There were no significant two- or three-way interactions involving Age and IQ test score group.

*Visuospatial Paired Associates Learning*

Even at the most difficult level of 8 items very few subjects failed to reach the 'all correct' criterion in ten trials or fewer; (14/771 = 1.8%) overall. The highest failure rate was in the 75–79 age band (4/128 = 3.1%). Other measures of performance, including total errors (omitting those subjects who failed to complete) or total trials to criterion and the first trial memory score produced comparable patterns as a function of age or intelligence group (fig. 3a, b). In each case, this test failed to distinguish between the two youngest groups or the two oldest groups, although the former performed significantly better than the latter. The middle age group (65–69) fell between these extremes.

*Spatial Working Memory*

Figure 4a, b shows the effects of age and IQ group on between search errors. All age groups, except the two youngest, differed significantly from all others. There was also a clear gradation of performance from IQ3 through IQ2 and IQ1 groups. There was a highly significant difference in search error scores between men and women (covarying for both age and intelligence score ($F_{1,709} = 20.21$, $p < 0.001$), with female subjects performing less well (mean error scores; males, 41.71; females, 48.97.

*Matching to Sample*
*(Visual Search for Designated Targets)*

Appreciable numbers of errors only occurred with the largest set size of 8. The effects of age and intelligence grouping are shown in figure 5a, b. There was no significant interaction between Age and IQ test score. As might be expected these effects were almost identical to those described for the simultaneous matching to sample task, in which similar stimuli were used.

Figure 5c, d shows latency as a function of set size. Data were analysed separately for set size 1 and for set sizes 2–8. For set size 1, there were significant effects of Age ($F_{4,698} = 16.90$) and Intelligence ($F_{2,698} = 11.20$) on latencies, but there was no significant interaction between them ($F_{8,698} = 0.49$).

As expected latencies increased with set size and with increasing age (table 5). However, there was also a significant Age × Set size interaction (over sets 2–8), showing that processing time per item was affected by increasing age. Figure 5c, d suggests that the two oldest groups showed a flattening of the function relating set size to reaction time, especially at set size 8. This occurred in parallel with an increase in errors for this level of difficulty.

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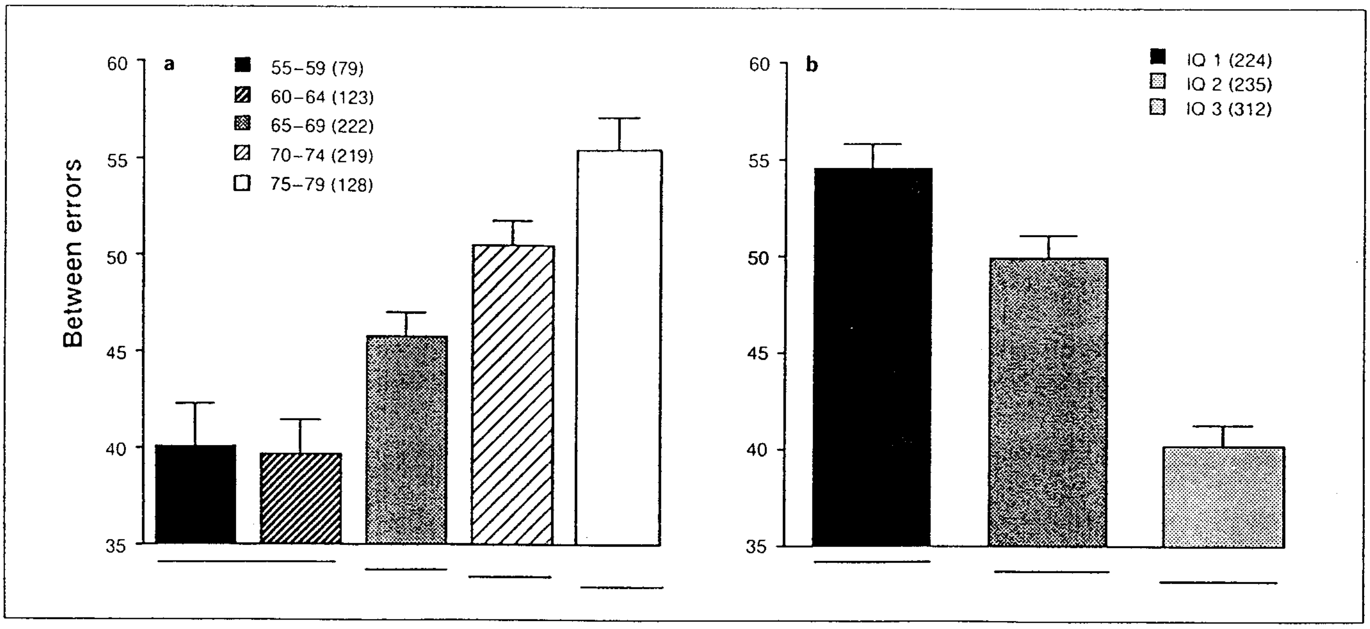
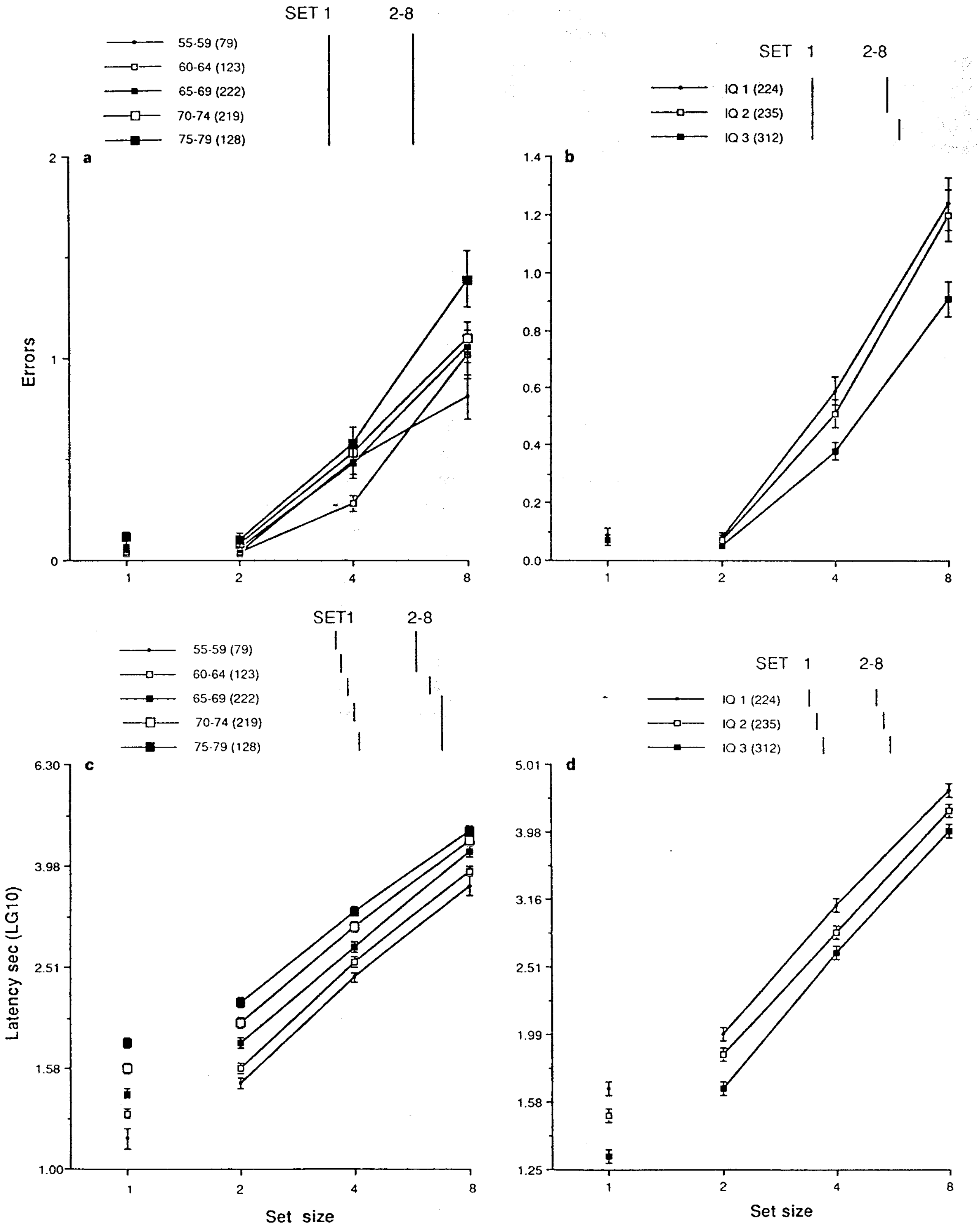



**Fig. 4.** Spatial working memory; between search errors, plotted for age (**a**) and intelligence score groups (**b**). Other conventions as in figure 1.

**Fig. 5.** Visual search, matching to sample. Accuracy and latency variables plotted separately for age (**a, c**) and intelligence score (**b, d**). Other conventions as in figure 1.



SET 1
2-8
55-59 (79)
60-64 (123)
65-69 (222)
70-74 (219)
75-79 (128)
a
Errors
SET 1
2-8
IQ 1 (224)
IQ 2 (235)
IQ 3 (312)
b
SET1
2-8
c
Latency sec (LG10)
Set size
d
Set size


5

**Table 5.** Three-way analyses of variance for MTS: summary

| | Accuracy | | Latency | |
|---|---|---|---|---|
| | F | d.f. | F | d.f. |
| Age | 2.46 | 4,755 | 12.22 | 4,755 |
| Intelligence | 4.30 | 2,755 | 12.56 | 2,755 |
| Set size | 240.80 | 2,1510 | 4854.46 | 2,1510 |
| A × I | 1.48 | 8,755 | 0.87 | 8,775 |
| A × S | 1.90 | 8,1510 | 4.23 | 8,1510 |
| I × S | 1.48 | 4,1510 | 1.67 | 4,1510 |
| A × I × S | 1.11 | 16,1510 | 1.31 | 16,1510 |

**Table 6.** Summary of loadings for CANTAB tests on factors 1-4 following factor analysis

| | Factor 1 | Factor 2 | Factor 3 | Factor 4 |
|---|---|---|---|---|
| Paired associates learning trials | 0.82 | | | |
| Paired associates learning memory score | 0.77 | | | |
| Pattern Recognition | 0.73 | | | |
| Spatial Recognition | 0.54 | | | |
| DMTS (sim) accuracy | | | | 0.71 |
| DMTS (del) accuracy | 0.63 | | | |
| DMTS latency | | 0.76 | | |
| MTS (visual search) accuracy | | | | 0.80 |
| MTS (visual search) latency | | 0.72 | | |
| Spatial working memory (between search) errors | | | 0.88 | |
| Spatial working memory (within search) errors | | | 0.77 | |

As in the simultaneous matching to sample test (see above), this suggests that increasing age does not merely alter the limits of speed and accuracy that people can attain but also, quite systematically, alters the speed-error trade-offs (compromises between speed and accuracy) that they choose to adopt. The effects of IQ test score ability contrast with those of age because, as the significant IQ test score group × Set size interaction shows, the lowest IQ score group took relatively longer to make correct decisions for set size 8. Again, there was no significant interaction of age and IQ test score group.

As in the simultaneous matching to sample task female subjects were significantly faster than males but, in this case, only at set size 4 ($F_{1,709} = 4.79$, $p < 0.05$).

*Factor Analysis* (table 6)

Eleven key variables were included in the analysis. The method employed was a Varimax rotation applied first to the entire data set (n = 771) and subsequently to 5 random samples, each of n = 200, in order to check the consistency of the factor structure within the population. Eight additional analyses were undertaken; one within each of the 5 age bands and one within each of the three IQ test score groups.

For the 5 random population samples, 4 factors were consistently extracted with eigenvalues above 1.00 (mean eigenvalues = 3.32, 1.65, 1.3, 1.03). These factor loadings were averaged over the 5 random samples, and accounted for an average of 60.52% of the variance. Table 6 gives the mean factor loadings for the 11 key variables. Only those variables loading above 0.50 are reported. The factor structure was checked against that obtained when all 771 subjects were included in a single analysis. Only one discrepancy was noted; for the total sample the DMTS accuracy score loaded more heavily on Factor 4 than on Factor 1.

The most parsimonious interpretation of the factor structure is that Factor 1 represents general learning and memory ability, Factor 2 represents speed of responding, Factor 3 represents executive processes including spatial working memory and Factor 4 respresents visual perceptual ability.

The factor structure remained consistent when tested separately within each age and IQ test score group. The main difference was that Factors 1 and 4 were readily distinguishable in all age groups except the youngest age band (55–59). However, it should be pointed out, this result is compromised by the relatively small n (= 79) for this group.

When age and intelligence scores were included in the analysis of all 771 subjects, these variables loaded most heavily on Factor 2 (speed of responding) and Factor 1 (learning and memory), respectively.

*Profile of Performance in the Lowest 5% of the Population*

The profile of performance was examined in those subjects performing within the lowest 5% in the various cognitive domains defined by the factor analysis, but excluding those subjects with scores less than 24 on the MMSE. The areas of cognitive function represented by Factors 1–4 above were defined by performance on variables with the highest loadings for each of the 4 factors. These were as follows; paired associates learning, total trials measure (Factor 1), latency on the DMTS (Factor 2), between search errors for the spatial working task (Factor 3) and errors on MTS (Factor 4). Comparisons across the 4 factors showed that most of these low IQ test scorers showed impairment on only 1 factor and that this pattern remained consistent across all 5 age bands. Thus, of 109 (14%) subjects performing below the 5th percentile on at least 1 of the 4 factors, only 10 (9.2%) were impaired on 2 factors. This represents only 1.3% of the total population of 771 subjects. No subject was impaired on more than 2 of the 4 factors.

*Low MMSE Subgroup*

Results of the 16 subjects with MMSE below 24, who had been excluded from the main analysis, were analysed separately. For Factor 1, the performance of 8 of the 16 subjects (50%) was below the 25th percentile, with only 3 of these (19%) falling below the 5th percentile; for Factor 2, the performance of 3 of the subjects fell below the 25th percentile and none fell below the 5th percentile; for Factor 3, the performance of 13 of the subjects fell below the 25th percentile and 3 fell below the 5th percentile; for Factor 4, the performance of 6 of the subjects fell below the 25th percentile and 3 fell below the 5th percentile.

Thus of these 16 low MMSE subjects, 2 scored below the 5th percentile on 1 factor, 2 scored below the 5th percentile on 2 factors and only 1 scored below the 5th percentile on 3 factors. The corresponding numbers for scores below the 25th percentile were 5, 6 and 4 subjects respectively. One subject performed above the 25th percentile on all 4 factors.

In summary, there is relatively little overlap between those subjects scoring below the accepted cut-off for dementia on the MMSE and those scoring in the bottom 5th percentile on the computerised tests.

## Discussion

The CANTAB battery was developed to extend paradigms developed to test animal models of the neurobiological and neurochemical changes that are believed to occur in humans who suffer from dementia of the Alzheimer type (DAT) and other pathologies that become increasingly common in later life. This standardisation of the CANTAB battery on a large, healthy population of older people shows that scores on subtests do sensitively differentiate between individuals of very diverse ages and levels of general ability.

The most important finding is that principal components analyses show that scores on CANTAB subtests fall into readily discriminable factors which can plausibly be identified with particular groups of cognitive functions that are known to be supported by distinct neural subsystems. For example, it is known that the spatial working memory test is especially dependent upon intact frontal lobes, whereas the pattern recognition memory test is unaffected by frontal damage but is sensitive to lesions of the temporal lobe [7, 28]. A second important point is that the effects of individual differences in age and IQ test performance do not appear as global and equivalent changes in scores on all factors but rather as local changes in some factors more than in others.

These findings contrast with predictions from current models of cognitive ageing which have been developed from principal component analyses of performance on very small subsets of cognitive tasks. Such analyses have generally yielded a single dominant factor which has been functionally reified as 'information processing rate'. This has been interpreted as evidence that changes in a single global performance characteristic of the central nervous system, 'mental speed', underlie all age-related changes in all other cognitive tasks [35, 36]. Parallel psychometric investigations which, curiously, have never cross-referenced data from cognitive gerontology, have also identified information processing rate as a functional reification of the single factor 'g' which Spearman [37] postulated as basic to all mental abilities [38–40]. This position has recently been modified to substitute 'working memory efficiency' for 'speed' as the single, basic performance characteristic that underlies individual differences in intelligence test performance [41] or in cognitive ageing [42]. However this shift in emphasis does not seem to indicate any relaxation of the assumption that individual differences in cognitive ability associated with IQ test performance or with age can best be described as points along a single continuum which can be identified with a particular, single performance characteristic of the central nervous system.

The idea that a single simple performance characteristic such as 'information processing speed' or 'working memory efficiency' underlies performance on all or most cognitive tasks is not well supported by the present data. At least 4 distinct and well separated factors are necessary to describe individual differences in performance on the CANTAB battery. The 1st factor can be identified with performance on tests of memory and learning, and accounted for about 28% of the variance. Additional analysis showed that this factor loaded on variance associated with individual differences in current scores on IQ tests. In contrast, the 2nd factor accounted for about 14% of the variance and loaded for speed of response in tests of memory and selective attention. This speed factor was more strongly associated with individual differences in age than in IQ test scores. The final 2 factors respectively loaded heavily on the test of spatial working memory (11% of variance) and on the visual perceptual aspects of the tests (8% of variance). We suspect that the loading of the 3rd factor on spatial working memory represents an executive function and this remains to be determined in our further analysis of tests of frontal lobe function.

This factor analysis suggests that the CANTAB battery does fulfil its primary aim of providing a componential analysis of particular cognitive functions. The clearest example of separation of cognitive abilities is the loading of both spatial and pattern recognition with the more complex test of visuospatial learning. The factor structure of the battery was stable within and between all the various age and IQ test score groups, with very rare exceptions. This suggests that the interrelationships between the various cognitive processes contributing to effective performance on CANTAB, remain relatively constant between ages 55 and 80 and across a wide individual variation in general ability, as assessed by IQ test scores.

Thus, from the point of view of interpretation of individual differences in performance, factor analyses of the CANTAB battery do confirm that differences between age and IQ test score groups are associated with individual differences in information processing speed and in the ability to learn and remember new information. However they also strongly suggest that neither of these two performance characteristics can, on its own, provide a *complete* description of the cognitive effects of ageing or of the functional bases of intelligence.

Analyses of data from individual tests in the CANTAB battery reinforce the point that individual differences in age and in IQ test score performance are better described in terms of *patterns* of differential changes across discrete performance indices rather than in terms of positions along a single continuous measure. Some performance indices, such as pattern recognition and reaction time, showed regular and continuous declines in performance with increasing age. Others, in particular spatial working memory, paired associates learning and spatial recognition memory, showed strikingly different trajectories of change with age. Performance on all these indices declined significantly between the 55–59 and 60–64 age bands. However, while spatial working memory continued to decline between the two oldest age groups, this was not the case for paired associates learning. It is unlikely that these differences in patterns of age effects on the two tasks are artifactual because performance on the paired associates task is very far from 'floor level' and this test has been shown to be very sensitive to deficits in several studies on clinical patients [5, 15]. Thus,we must conclude that spatial working memory performance is more sensitive to advancing age beyond 65 years than is either paired associates learning or spatial recognition memory. Conversely, delayed matching to sample at the longest delay (12 s) is more sensitive to age changes between 55 and 64 years.

Some trends in age-related changes in performance were obscured by particular characteristics of CANTAB subtests. The main example was the delayed matching to sample test, in which there was a delay-dependent decline in accuracy of performance from the younger age bands, but not in older age groups (fig. 2a). Inspection of figure 2a and additional analyses suggest that performance accuracy significantly declines as delay intervals increase from 0 to 4 s but thereafter reaches a baseline level of about 75% correct, with the result that the delay function is compressed. The most obvious explanation of this phenomenon is that subjects are using a mnemonic strategy which allows them to retain high levels of accuracy even at long delays. For example it seems likely that they encoded the patterns in terms of verbal labels derived from their colours. This would have the effect that choice at matching would be reduced from 4 to 2 stimuli; i.e. to a choice between the target stimulus and the same-coloured distractor. Evidence for this is that subjects' errors showed more confusions between targets and same colour distractors than between targets and same shape distractors. The superior performance of the high IQ group IQ3 may also be taken to reflect their greater use of efficient verbal encoding strategies, although it should be pointed out that the test as a whole was relatively insensitive to differences associated with IQ test scores. The verbal encoding hypothesis is testable, since if it is correct the imposition of an articulatory suppression task concurrently with the DMTS task should interfere with verbal recoding and result in sharply reduced performance.

As might be expected from many earlier demonstrations that targets among distractors are located by serial self-terminating search [43] there was a very strong linear relationship between target detection time and the number of items on the displays in the simultaneous matching to sample (visual search) task. Younger subjects made few errors and there was some evidence that age not only brought about an overall slowing of performance but also altered processing time for individual items on displays. However, this was the opposite of the usual age complexity interaction documented by Cerella [44], since the slopes of the reaction time set size functions *reduced* rather than increased in the older age groups. These older groups also showed significant increases in error rates with set size, suggesting that as displays became more complex they increasingly began to sacrifice accuracy to maintain speed. Once again it appears that choice reaction time tasks do not yield 'pure' indices of individual differences in a single performance characteristic, 'information processing speed'. Latencies and accuracies must be analysed together, as joint indices that reflect the particular compromise that individuals choose to adopt between the maintenance of speed and of accuracy. In the matching to sample (visual search) task the oldest groups were not simply slower than the young; they also adopted different speed-error trade-off criteria. It is particularly interesting that differences in trade-off strategy in older groups cannot be put down to declines in their general cognitive ability, as assessed by IQ test performance. The low IQ group (IQ1) did not behave like elderly subjects and there was no suggestion that the choice of speed-error trade-off strategy varied between IQ test score groups.

Examination of gender differences showed that there were some significant differences that could not be explained in terms of the slightly higher IQ test score of the male sample or in terms of age differences. While there was no significant difference in accuracy between men and women on the pattern recognition task, men were slightly but significantly better than women at spatial recognition. Men also had a clear advantage over women on the spatial working memory task. This cannot be explained as a consequence of a subject selection bias favouring men, since there was no difference in overall IQ test scores between the men and women in this population. Further, in contrast to their poorer performance at spatial tasks, women were slightly but significantly faster than men at simultaneous matching to sample. Previous studies have found that a female advantage in information processing rate gradually emerges as age increases within the range represented in this population. This has been taken as evidence that the well known advantage in longevity enjoyed by women over men entails a correspondingly slower rate of central nervous system ageing [45]. It therefore seems possible to describe this pattern of results as evidence for a functional dissociation between two performance indices, spatial memory and information processing speed, both of which have been shown in this study to be exceptionally sensitive to biological ageing. It can be argued that women age more slowly than men, and so retain their information processing ability until later in life, but apparently continue in old age to suffer from the slight, overall disadvantage in spatial problem solving that has been repeatedly demonstrated over the last 50 years [see 46 for a review].

In order to justify its use in demented populations as a possible clinical tool, it is important not only to standardize the battery on a large sample of elderly volunteers, as we have done here, but also demonstrate its utility in the detection and diagnosis of dementia, in comparison with commonly used clinical instruments, such as Folstein's MMSE [34]. This would clearly require a longitudinal study which is ongoing and cannot be reported in detail at present. However, it is of interest to compare the performance of patients at the low (<5th percentile) end of the distribution for CANTAB and MMSE. In order to reach this criterion for CANTAB it was decided to concentrate on those tests with the highest factor loadings for each of the 4 factors identified from the factor analysis and to select those subjects scoring below the 5th percentile on two or more of these tests (in order to satisfy the common diagnostic criterion for DAT that performance must be shown to deteriorate in more than one cognitive domain).

The interesting result to emerge from this analysis is that there was relatively little overlap between individuals scoring in the dementing range (i.e. <24 on the MMSE) and in the lowest 5th percentile on the CANTAB battery. The implication is that the two sets of tests are measuring different aspects of cognitive impairment, and this might be useful for detecting dementia in those individuals with high estimated IQs who score above the 24 cut-off on the MMSE. For this reason, it will be particularly interesting to follow both subsets of subjects longitudinally.

## Conclusions

The CANTAB battery was designed on the premise that cognitive functions are both diverse and modular in the sense that they are supported by overlapping yet distinct sets of neural structures which may be differentially affected by different forms of CNS pathology. The subtests were therefore selected to assess putatively independent performance indices. The first reassurance from this standardisation is that the principal components analyses do indeed show that the performance indices derived from the battery can be separated into 4, well-distinguished factors, each of which can be plausibly identified with different cognitive functions. A second reassurance is that the factor structure of the CANTAB battery remains markedly consistent across age groups from 55 through 80, and across groups with high, medium and low scores on IQ tests. A third reassurance is that because individuals' IQ test scores show differential loadings across the 4 factors, the test battery does not simply pick up the same range of individual differences that are detected by standard tests of general intellectual ability.

By these same tokens, these analyses also make a theoretical contribution to discussions of cognitive ageing and of the functional bases of individual differences in intelligence. They show that 'cognitive age' is not merely a synonym for 'lower intelligence' because all differences in cognitive performance between age groups cannot be accounted for in terms of variance in performance on tests of general ability. They further show that variations in cognitive performance associated with cognitive ageing or with performance on intelligence tests are not well described in terms of differences along a single performance parameter, whether this is identified as 'information processing rate' or as 'working memory efficiency'. The cognitive effects of ageing and of individual differences in intelligence must, rather, be described in terms of differential patterns of performance on discrete groups of cognitive tasks. To the extent to which the CANTAB battery succeeds in its aim of providing separate assessments of the relative integrity of different functional neurophysiological and neuroanatomical subsystems it also provides the beginnings of a methodology for investigating the biological and functional bases of intelligence and of ageing of the central nervous system.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