THE QUARTERLY JOURNAL OF EXPERIMENTAL PSYCHOLOGY, 2002, *55A* (4), 1273–1293

Syllogistic reasoning and cognitive ageing

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Gilinsky and Judd (1994) demonstrated that age-related impairment in syllogistic reasoning was in part due to reduced working-memory capacity. A total of 30 older (average age 66 years) and 34 younger persons (average age 24 years) were tested on syllogisms of various types as well as on other measures. Syllogistic reasoning was significantly correlated with education, processing speed, word span, and word fluency. Correlations with visuo-spatial processing and random letter generation were just short of significance. Syllogistic reasoning performance declined with age, although the deficit was no longer statistically significant following control for age-related differences in information-processing speed. On the other hand the inclusion of word fluency as an additional covariate boosted the apparent age effect, returning it to statistical significance. Thus it is possible that cognitive processes outside of working memory might underpin at least part of the apparent age deficit. This possibility is evaluated in the light of neuropsychological evidence implicating the prefrontal cortex in both the processing of syllogisms and more generally in cognitive ageing.

Age-related deficits in working-memory functioning have been widely documented (e.g., Campbell & Charness, 1990; Salthouse & Babcock, 1991). In turn, these deficits have been held to be responsible for a range of other age-related impairments—for example, in matrix reasoning (Salthouse, 1993), prospective memory (Cherry & LeCompte, 1999), language comprehension (Van der Linden et al., 1999), and in syllogistic reasoning (Gilinsky & Judd, 1994). Age-related differences in syllogistic reasoning are the focus of the present paper. More specifically, it is of interest to determine those parts of the working-memory system that mediate age-related impairments in syllogistic reasoning. To set the context for the present study, a brief outline of research into syllogistic reasoning is provided, followed by an account

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The authors are grateful to Peter Warr for his contribution during the early stages of this investigation and to Jonathan Evans, Patrick Kyllonen, and an anonymous reviewer for comments on earlier versions of this manuscript.

http://www.tandf.co.uk/journals/pp/02724987.html DOI:10.1080/02724980244000107

of the working-memory system. These two aspects combine to form a basis for investigating age effects in this important area of cognition.

Interest in syllogistic reasoning dates back to Aristotle and the ancient Greeks, and in more recent times pre-eminent figures such as Piaget have argued that the logical processes underpinning syllogistic and propositional inference form the basis for all significant forms of adult reasoning (Inhelder & Piaget, 1958). Johnson-Laird (1983) has proposed that rather than relying on the existence of some logical propositional calculus as an explanation of the mental processes that underpin reasoning, an account in terms of the construction of mental models constitutes a better theory. Much of the research into syllogistic reasoning has in recent years focused on the adequacy of mental models theory as an explanatory system.

Johnson-Laird (1983) argues that reasoning is accomplished by means of constructing mental models of the premises and testing inferences or conclusions against these models. In the context of syllogistic reasoning some problems are relatively simple, requiring the construction of only one model. For example the pair of premises:

Some of the A are B
and
All of the B are C

can be accommodated within a single model, from which it follows that

Some of the A are C

as there is no alternative model of the premises that violates this conclusion. On the other hand the pair:

All of the B are A
and
None of the B are C

Initially gives rise to a model that is consistent with the proposition that

No C are A

this in turn requires the construction of a second model, which, remaining consistent with the premises, falsifies this conclusion. This second model, however, leaves open the propositions that

Some of the C are not A
as well as
Some of the A are not C

which in turn requires the construction of a third model, which leaves only the latter of these two conclusions as valid (see Johnson-Laird, 1983, pp. 98–100). Thus this pair require the construction of three models to derive a valid conclusion. The construction and temporary retention of these models uses up cognitive resources, in particular working memory, and thus three-model problems require more resources than one-model problems and are thus perceived to be more difficult.

In fact recent research suggests that many people construct only a single model of the premises and fail to search for counter-examples or alternative models, thus giving rise to faulty reasoning (Evans, Handley, Harper, & Johnson-Laird, 1999; Newstead, Handley, & Buck, 1999). In fact, those persons who were more likely to search for counter-examples when attempting to solve reasoning problems tended to outperform those who did not (Handley, Dennis, Evans, & Capon, 2000).

A number of other factors appear to affect performance in syllogistic reasoning. For example, elaboration of the premises can facilitate performance, especially with multi-model problems. In effect elaboration appears to reduce the number of models that need to be constructed to derive a valid conclusion (Newstead & Griggs, 1999), thereby reducing the strain on working-memory resources. More generally, limitations in working-memory capacity, both phonological and spatial, were associated with a tendency to generate more biased responses in syllogistic reasoning, especially for problems requiring multiple models (Quayle & Ball, 2000). Thus overall, the outcomes of a number of recent studies are consistent with an account of syllogistic reasoning in terms of mental models theory and working-memory capacity.[1] However, what is the exact nature of working memory?

Among the best known accounts of working-memory functioning is Baddeley's (1986) multi-component model consisting of two "slave systems": the phonological or articulatory loop, and the visuo-spatial sketchpad, together with a modality-free central executive mechanism. There is a considerable volume of research evidence demonstrating that cognitive performance can usefully be described in terms of the operation of separate sub-systems of this kind (see Baddeley, 1992, for a review of the literature).

For example, a number of studies utilizing a dual-task methodology have shown that the central executive is implicated in various aspects of cognitive performance. For example, the central executive has been shown to be involved in conditional reasoning (Toms, Morris, & Ward, 1993), in generating connected sequences of stimulus-independent thought (Teasdale et al., 1995), and in syllogistic reasoning (Gilhooly, Logie, Wetherick, & Wynn, 1993; Gilhooly, Logie, & Wynn, 1999).

Using other experimental procedures it has been found that the central executive is subject to age-related deficits. For example, relative to their younger counterparts, in random letter generation (a task believed to tap the central executive) older persons are significantly less random at all production rates (Fisk & Warr, 1996; Van der Linden, Beerten, & Pesenti, 1998). Furthermore, using a consonant updating task developed by Morris and Jones (1990), Van der Linden, Bredart, and Beerten (1994) found that older persons were worse specifically at the updating component, again consistent with an age-related decline in central executive capacity.

Thus to sum up, the central executive component of working memory has been shown to be implicated in syllogistic reasoning (Gilhooly et al., 1993, 1999). Age-related impairments have

[1] Some of these findings can also be accounted for in terms of the application of general-purpose inference rules, i.e., the application of some form of internalized mental logic, although as noted earlier Johnson-Laird (1983) is critical of accounts of deductive reasoning in these terms.

been documented in both central executive functioning (e.g., Fisk & Warr, 1996) and in syllogistic reasoning (Gilinsky & Judd, 1994). It seems at least possible therefore that the central executive might mediate age-related deficits in syllogistic reasoning. Gilinsky and Judd's work has shown that the ability to generate solutions to abstract syllogisms declines with age and that measures of global working-memory functioning account for at least part of this impairment. Equally it seems clear that multi-model problems, as they are more demanding of working-memory resources, should be particularly vulnerable to any reduction in working-memory resources that is associated with age.

It remains unclear, however, which components of the working-memory system are implicated. Visuo-spatial, phonological, and executive processes have been identified as being involved in syllogistic processing (Ford, 1995; Gilhooly et al., 1999; Quayle & Ball, 2000). Thus it is possible than any or all of these processes might mediate age-related changes. With this is mind, the present study seeks to investigate the role of the component parts of working memory in mediating any observed age deficit.

In addition, the potential role of basic information-processing speed in mediating age differences in syllogistic reasoning are also investigated. Salthouse (2000) has argued that a slow-down in basic information-processing speed is responsible for a range of observed age-related deficits in various aspects of cognitive functioning. In particular, Salthouse and Babcock (1991) found that age differences in global measures of working memory, such as those used by Gilinsky and Judd (1994), were largely attenuated following control for the effects of information-processing speed. If Salthouse and Babcock are correct in asserting that the slow-down in information-processing speed is responsible for the age-related impairment in working-memory functioning, perhaps the same slow-down might also be responsible for the age-related deficit in syllogistic reasoning. This possibility was not addressed in Gilinsky and Judd's original paper.

Apart from these aspects, Gilinsky and Judd's (1994) research involved participants for the most part educated to university level, many of whom were recruited through the Phi Beta Kappa Associates academic honours society (which is typically limited to those graduating in the top 10% of their class). Thus the authors note that "The resulting sample is obviously not representative of the general population" (p. 359). The present study uses a more balanced sample with a significant proportion of both younger and older persons educated to no more than high-school level.

The expectations underpinning the present study are that, consistent with Gilinsky and Judd's (1994) results, syllogistic reasoning performance will decline with age and that this decline will be especially pronounced for multi-model problems. Furthermore, the age-related variance will be reduced to below statistical significance following control for the mediating effects of age-related deficits in working-memory processes, in particular information processing speed and executive functions.

Method

Design

The expectations noted earlier were tested using repeated measures multivariate analysis of variance (MANOVA, profile analysis) with problem type (one-model; no valid conclusion, NVC; and three-model) within participants and age category with two levels, corresponding to older and younger persons, between participants. Dependent variables were the percentage of correct responses for one-model, NVC, and three-model problems. Subsequently, this procedure was repeated incorporating a range of covariates representing aspects of working-memory performance and information-processing speed. These were entered individually and jointly to establish whether the age effect remained statistically significant.

Participants

A total of 34 individuals aged between 20 and 33 years (19 male, 15 female, average age 24 years) and 30 persons aged between 59 and 74 years (14 male, 16 female, average age 66 years) participated in the study. All participants were recruited from the University of Sheffield participant panel. Each was paid £12 for participating in the study.

Equipment and measures

Various background measures were taken, including the number of years of full-time education and a self-report measure of perceived health defined on a 5-point scale ranging from 1 "excellent" to 3 "average" and 5 "poor". The constructs of interest were measured through a range of computer-based and pencil and paper tasks as follows.

Processing speed. Two measures of speed were obtained as described by Salthouse and Babcock (1991). The first involved a *letter comparison speed* task in which participants were presented with two rows of letters on a computer screen. They were asked to classify these as quickly as possible as "the same" or "different" by pressing the "/" key if the two rows were the same and the "z" key if they were different. The two rows of letters were identical in half of the trials but differed by one letter only in the other half. In each trial, letters were chosen randomly from the set of consonants, and the position of the non-identical letter within the string was randomized. For the first 30 s, each presented row consisted of three letters, for the next 30 s each row contained six letters, and for the third 30 s each row consisted of nine letters. For each level of complexity (three, six, or nine letters) the computer kept a record of the number of correct responses. This task was repeated three times with the first occasion treated as a practice trial. Scores for Trials 2 and 3 at each of the three levels of complexity were standardized and subsequently combined with the equivalent values for the pattern comparison task to form, a single measure as indicated later.

The *pattern comparison speed* task was structured in exactly the same way as the letter comparison task. However, the stimulus was a matrix potentially consisting of a basic grid of nine cells (three across and three down). A line segment defined the border of each cell. The targets were made up of three, six, and nine line segments randomly selected from the basic grid. Two patterns were displayed, one in the top and one in the bottom half of the screen. As in the letter task, the objective was to classify as many pairs as "the same" or "different" within a fixed time period. For the first 30 s, patterns consisted of three line segments, for the next 30 s they comprised six line segments, and for the third 30 s they were made up of nine line segments. Following the procedure set out above, the performance data for Trials 2 and 3 at all three levels of complexity were standardized, and combined with the equivalent standardized scores for the letter comparison task to form a single measure of information-processing speed (a similar approach was adopted by Salthouse & Babcock, 1991).

Working-memory span. Conventional measures of reading span (based on the measure developed by Daneman & Carpenter, 1980) and computation span (based on a measure employed by Salthouse & Babcock, 1991, and Turner & Engle, 1989) were utilized. Both measures are assumed to tap all three components of working memory. They require reading under conditions of increasing memory load, which is likely to place demands on the visual and phonological systems, and the concurrent requirement for storage and processing is believed to involve the central executive (Engle & Conway, 1998). In the case of reading span, a person was required to answer a question about each of several sentences as it appeared on the screen. An answer book was supplied, with questions framed in multiple-choice format. For example, the following sentence was among those used: "At Wimbledon it rained during June, spoiling the tennis", with the following question and alternatives: "When did it rain? August ....; June ....; May ....". After all sentences in a set had been presented, the person was required to write down the last word of each sentence in the answer book in the order in which they occurred. The task started with three sets containing just one sentence, then the set size was increased by one sentence at a time to two, three, four, and five sentences, and so on. *Reading span* was defined as the maximum number of end-of-sentence words successfully recalled on at least two out of three trials, with the added requirement that the sentence comprehension questions had been answered correctly.

The computation span task was structured in an identical fashion. However, the sentences were replaced by simple arithmetic problems, and participants were required to recall the last digit of each problem in sequence. *Computation span* was thus defined as the maximum number of digits recalled in two out of three trials, with the requirement that the corresponding arithmetic problems had been answered correctly.

Central executive functioning. This was assessed through a random-letter generation task closely based upon the procedure described in Baddeley (1966). However, a computer display and concurrent auditory signal was used to pace responses. Participants were asked to speak aloud letters in a random sequence. They were told to avoid repeating the same sequence of letters, to avoid producing alphabetical sequences, and to try to speak each letter with the same overall frequency. Individuals were asked to produce three sets of 100 letters; one set was to be produced at the rate of one letter every 4 s, another set at one every 2 s, and the third set at one every 1 s. The order in which participants produced the sequences (i.e., 4-, 2-, or 1-s intervals) was randomized. Responses were recorded on an answer sheet by the experimenter.

This task yields three measures of non-randomness. The first is the number of repeat sequences, which corresponds to the number of times any letter pair is repeated, summed over all such occurrences. The second is the number of alphabetical sequences, which relates to the number of letter pairs that are alphabetically ordered. Finally, the third is a percentage measure of redundancy. If individuals were truly random, each letter of the alphabet would be generated the same number of times in any given sequence. Percentage redundancy represents the extent to which this is *not* the case—that is, the extent to which some letters occur more often than others. It is computed following the procedure set out by Baddeley (1966). For each of these three measures, the higher the score the less random are the responses. Thus each person generated three scores at each of three production rates (4-s, 2-s, and 1-s). These nine values were combined into a single measure following standardization.

In addition to random generation, two other executive measures were administered: the Wisconsin card sort task (WCST) and the Chicago word fluency test (CWF). Both are considered to tap frontal lobe executive processes (see, e.g., Barcelo, Munoz-Cespedes, Pozo, & Rubia, 2000; Kolb & Whishaw, 1985). The WCST requires individuals to sort cards into categories according to some criteria based on the colour, shape, or number of stimulus items on the card. After 10 consecutive cards have been successfully sorted the criterion is changed without warning, and the individual has to deduce the new sorting rule. The task yields a number of measures. In the present study the two performance measures used are the average number of perseveration errors per sorting category achieved and the average number of trials per category attempted. Perseveration errors occur when the individual continues to sort according to the old criteria or category when this is no longer valid. Each card so placed counts as an error. The number of trials per category is equal to the number of cards placed before that category is successfully achieved. Thus the minimum score on this measure is 10, as it is a requirement of the task that ten *consecutive* cards are successfully sorted before the category is changed. So if an individual placed four cards before successfully deducing the new sorting rule, then that person's score for that particular category would be 14.

The CWF task has two components. First the individual is asked to write down as many words as possible beginning with the letter "s" in 5 minutes and as many four-letter words beginning with the letter "c" in 4 minutes. In the present study both elements are scored separately. Duplicate words and plural words formed by adding the letter "s" were excluded.

Phonological loop functioning. This aspect of Baddeley's model was assessed through word span and digit span tasks (Baddeley, 1986). For the *word span* task, words (all nouns of one syllable) were displayed sequentially on the computer screen, each for 1.25 s, and individuals were required to recall the words in the order in which they were presented. Presentations started with three sets of two words, rising to three sets of three, four, and five words, and so on, until the person made mistakes in recall in two of the three sets at a given level. Word span was defined as the maximum number of words successfully recalled on at least two out of three trials. Responses were hand-written by the participant in an answer book. The *digit span* test was administered in an identical fashion.

Visuo-spatial functioning. Two separate measures were administered, one assessing visual performance the other spatial. The visual task was based on one devised by Salthouse, Kausler, and Saults (1988). Participants were shown a computer display consisting of a 5 × 5 grid with 7 of the 25 cells highlighted. The seven highlighted cells were randomly positioned, and the resulting pattern was displayed for 3 s. The participant was then asked to indicate the position of the seven highlighted cells on a blank grid in an answer book provided for this purpose. Six such patterns were presented. The score was the number of patterns successfully reproduced. The spatial measure was based on Brooks' (1967) spatial sequences task. This requires participants to generate a spatial sequence by following a set of instructions spoken aloud by the researcher. The participant is presented with a blank 4 × 4 grid, in which one cell, known as the "starting square" is highlighted. The researcher then reads aloud a set of instructions that define a spatial sequence within the grid—for example, "in the starting square put a 1, in the next square down put a 2, in the square to the right put a three, etc.". Immediately after the researcher has voiced the instructions, participants are required to record the sequence (which consists of eight such movements) in an answer book provided for this purpose. Eight such sequences are presented, and the score is based on the number out of eight successfully reproduced.

Syllogistic reasoning task. Participants attempted to generate solutions for 4 one-model, 4 three-model, and 4 NVC syllogisms. Scores were based on the number of correct solutions produced or, in the case of the NVC syllogisms, a response was deemed correct when the participant indicated that no valid conclusions were possible. The syllogisms used in the study were taken from the list set out by Johnson-Laird (1983). A total of 4 one-model, 4 three-model, and 4 NVC syllogisms were selected. In general, according to Johnson-Laird, NVC syllogisms require either two or three models in order to derive the correct solution. In the present study two of the NVC problems were two-model and the other two were three-model problems. Thus in terms of the number of models required, the three-model problems were the hardest, the one-model problems the easiest, and the NVC problem types intermediate in difficulty. The actual syllogisms used in the present study were selected in a quasi-random manner (i.e., randomly, subject to the requirement that there were four of each type, as noted earlier). They are reproduced as follows.

	Syllogism	*Type*	*Conclusion*
1.	Some of the B are A All the B are C	1M	Some of the C are A Some of the A are C
2.	None of the A are B Some of the B are C	3M	Some of the C are not A
3.	Some of the B are A All the C are B	NVC	NVC
4.	All the B are A None of the C are B	3M	Some of the A are not C
5.	All the B are A None of the B are C	3M	Some of the A are not C
6.	Some of the B are not A Some of the B are C	NVC	NVC
7.	Some of the A are B None of the B are C	3M	Some of the A are not C
8.	Some of the A are B All the B are C	1M	Some of the A are C Some of the C are A
9.	None of the B are A Some of the C are not B	NVC	NVC
10.	All the A are B None of the C are B	1M	None of the C are A None of the A are C
11.	None of the A are B All the C are B	1M	None of the C are A None of the A are C
12.	Some of the A are B Some of the C are B	NVC	NVC

Participants were introduced to the concept of a syllogism, and examples were provided (some concrete and some abstract). Examples and explanations were also provided of some correct and some incorrect inferences. In addition, Venn diagrams were provided demonstrating possible representations for the two syllogisms:

1. All A are B, All B are C
2. Some A are B, Some B are C.

Participants were told to generate as many conclusions as possible for each pair of premises. They were told that no pair generated more than two valid conclusions, that some only generated one, and others yielded no valid conclusions. In addition they were provided with a list of the eight possible solutions that can be generated over all legitimate pairs of premises. The actual questionnaire presented to participants is reproduced in the Appendix.[2]

Procedure

The tasks were administered in the following order: health/education questionnaire, WCST, syllogistic reasoning, random letter generation, tasks to measure processing speed (letter and pattern comparison), word span, Brooks spatial sequences, pattern memory, CWF, digit span, computation span, and

[2]The background information on syllogisms provided to participants was in part based on the description given by Anderson (1990).

finally reading span. All participants were allowed a rest-break half way through, and additional breaks were offered where deemed necessary by the researcher or requested by the participant. Overall, between 2 and 3 hours were required to complete this sequence. Individuals were finally informed about the purpose of the experiment and were asked for their comments.

Results

Units of measurement for the variables assessed in the present study are for the most part described in the method section. Means and standard deviations are set out in Table 1. It should be noted that a high score on the random generation and on the WCST tasks is indicative of poor performance. In all other cases, the higher the score the better the performance. With regard to syllogistic reasoning, the maximum score possible for the one-model problems was 8 (two valid conclusions per syllogism); for the three-model and NVC syllogisms maximum scores were 4 in both cases. The overall measure for syllogistic reasoning in Table 1 is expressed in terms of the average percentage correct over the three different problem types. Thus a person achieving 40%, 5%, and 30% correct for the one-model,

TABLE 1
Syllogistic reasoning and working memory performance by age group

	Young group		*Old group*		*Correlation with:*	
	Mean	*SD*	*Mean*	*SD*	*Syllogistic reasoning*	*Age*
Age[a]	23.71	3.49	65.93	3.64	–.319**	
Syllogistic reasoning[b]	42.03	20.47	29.44	17.16		–.319**
Health	2.71	0.94	2.28	1.27	.027	–.190‡
Education[c]	14.32	3.01	12.80	3.46	.299**	–.233*
Processing speed	0.57	0.75	–0.36	0.65	.248*	–.558***
Word span	4.91	0.97	4.50	0.63	.217*	–.245*
Digit span	7.21	1.43	6.70	1.44	.113	–.176‡
Visual recall	2.44	1.33	1.07	1.11	.085	–.492***
Spatial processing	7.47	0.96	5.53	1.85	.188‡	–.561***
Random letter generation	0.00	0.49	0.20	0.64	–.180‡	.182‡
WCST: Trials per category attempted	15.86	5.35	26.64	17.24	–.122	.403***
WCST: Perseveration errors per category achieved	1.29	0.63	1.68	1.18	–.167‡	.209*
CWF: letter S	51.91	11.66	47.73	13.19	.227*	–.168‡
CWF: letter C	20.35	7.17	22.20	7.82	.224*	.124
Reading span	2.56	0.79	1.80	0.48	.159	–.502***
Computation span	2.50	0.75	1.93	0.69	.069	–.369**

Note: $N = 64$.
[a]In years.
[b]Percentage correct.
[c]Years full time.
* $p < .05$; ** $p < .01$; *** $p < .001$; one-tailed in all cases.
‡ $p < .10$; one-tailed.

three-model, and NVC problems, respectively, would receive an overall score of 25 (i.e., 40+5+30 = 75 divided by 3).

It is clear from Table 1 that syllogistic reasoning is significantly correlated with age category (older persons achieve fewer correct answers) and with years of education (those persons with more years of education tend to do better). It is also positively correlated with word span, information processing speed, and with both word fluency measures. Those persons tending to do well in any of these also tend to perform well in the syllogistic reasoning task. The correlations between syllogistic reasoning and, respectively, spatial processing, random letter generation, and WCST perseveration errors were all just short of statistical significance. Age category was significantly correlated with most of the measures included in Table 1. In all but one case (the CWF letter C task) older persons performed at a lower level than that of their younger counterparts.

The central focus of the study is age-related differences in syllogistic reasoning, and it is clear from Table 1 that there is a significant decline in performance with age. Averaged over all three problem types, older persons managed a success rate of almost 30% whereas their younger counterparts produced 42% correct responses. Table 2 shows that this age-related deficit was present for all three problem types: one-model, NVC, and three-model problems (although not significantly so for the last of these). Confirming this apparent trend, repeated measures MANOVA yielded a significant effect of age, $F(1, 62) = 7.00$, $p < .01$. There was also a significant effect of problem type, Wilks' lambda = 0.376, $F(2, 61) = 50.59$, $p < .001$. Consistent with existing accounts of syllogistic reasoning including mental models theory, performance was best with one-model problems, intermediate with NVC problems, and worse with three-model problems. The age by problem type interaction was not significant, Wilks' lambda = 0.979, $F(2, 61) = 0.66$, $p > .05$. Thus the magnitude of the age deficit did not differ significantly over the three problem types.

Although an age effect was obtained it remains possible that other background variables that co-vary with age might in fact underpin the effect. In the present study controls were introduced for the potential effects of health-related differences between the two samples. However, it is clear from Table 1 that education is correlated with syllogistic reasoning performance, and as older persons have fewer years of education than the younger group it is possible

TABLE 2
Syllogistic reasoning and working-memory performance by age group

	Percentage correct				*Correlation with:*	
	Young group		*Old group*			
Syllogistic reasoning	*M*	*SD*	*M*	*SD*	*Age alone*	*Age with control for CWF–C*
One model	59.19	25.99	47.50	25.93	–.223*	–.254*
Three model	19.12	26.87	11.67	20.48	–.155	–.182‡
No valid conclusions	47.79	33.92	29.17	29.42	–.284*	–.302**

Note: $N = 64$.
*$p < .05$; **$p < .01$.
‡$p < .10$.

that the age effect might be attributable to the difference in the education level between the two groups. Table 3 however, clearly demonstrates that the age effect, although reduced by some 30%, remains statistically significant following control for this difference. Although health and educational differences can be excluded as a potential source of the age differences that have been obtained, it must nonetheless be acknowledged that in quasi-experimental designs of this kind other unforeseen background factors might underpin the apparent age effect.

The second broad objective of the present study was to establish whether working-memory impairment might be responsible for the obtained age effect in syllogistic reasoning. Consistent with expectations, information-processing speed, which is believed to underpin age differences in working-memory performance, reduced the age-related syllogistic reasoning deficit to below statistical significance.

What about the moderating effects of the various components of working memory? Table 3 shows that age accounted for just over 10% of the variance in syllogistic reasoning ($\eta^2 = .101$). It is clear that control for age differences in word and digit span as well as age differences in visual and spatial processing only marginally reduce the age-related variance, which remains significant in both cases. Thus it appears that those deficits in syllogistic reasoning attributable to age are not mediated by age-related decrements in either the phonological loop or the visuo-spatial system.

What of the central executive component of working memory as assessed by random generation and the CWF and WCST tasks? It is apparent in Tables 1 and 3 that random letter generation is not significantly correlated with syllogistic reasoning, nor does the process substantially mediate age-related changes in performance. What Table 3 does reveal is that control for the frontal lobe executive measures (CWF and WCST) actually increases the age-related variance in syllogistic reasoning. Subsequent analyses demonstrated that this apparent suppressor effect is attributable to one of the CWF measures—that is, the sub-task in which

TABLE 3
Effects of age on syllogistic reasoning following controls for various aspects of working memory

Covariates	*Sums of squares attributable to age*	*Effect size for age (eta squared)*	*df*	*F value*
Age only (no covariates)	7578.51	.101	1,62	7.00**
Health and education	4917.16	.072	1,60	4.68*
Processing speed	3523.04	.050	1,61	3.23‡
Word and digit span	5578.37	.078	1,60	5.10*
Visual and spatial processing	5512.98	.077	1,60	4.97*
Random letter generation	6303.18	.087	1,61	5.83*
WCST and CWF measures	8782.69	.129	1,58	8.62**
Random letter generation, WCST and CWF measures	8215.79	.122	1,57	7.93**
Reading and computation span	5915.87	.081	1,60	5.31*
All of the above	5222.34	.092	1,48	4.84*

* $p < .05$; ** $p < .01$.
‡ $p < .10$.

persons are allowed four minutes to generate as many four-letter words as possible beginning with the letter "c" (CWF–C). Specifically, repeated measures MANOVA—with the syllogistic reasoning outcomes as the dependent variables, age between participants, and CWF–C as the sole covariate—produced a significant incremental age effect, $F(1, 61) = 8.98, p < .01, \eta^2 = .128$. Interestingly the global measures of working-memory functioning, computation, and reading span were not significantly correlated with syllogistic reasoning, nor did they significantly attenuate the age effect (see Tables 1 and 3).

Only information-processing speed (when entered as the sole covariate) reduced the age effect to below statistical significance, and it is noteworthy that this outcome was reversed when processing speed was included along with all of the other covariates including the suppressor variable CWF–C. Thus by way of summary, Table 3 reveals that although the age effect in syllogistic reasoning was reduced to below statistical significance following control for the effects of information-processing speed, when the word fluency measures were also included as covariates the residual age effect actually increased in magnitude and again became statistically significant.

Discussion

The present study confirms the results of Gilinsky and Judd (1994) in that relative to their younger counterparts older persons were found to be significantly impaired in syllogistic reasoning. Gilinsky and Judd found that the correlation between age and performance was –.349.[3] This compares with –.319 in the present study. However, the predicted age by problem type interaction was not significant. Older persons were no more impaired on three-model than with single model syllogisms. This outcome appears to be inconsistent with the findings of Johnson-Laird (1983), who argues that in processing more complex syllogisms individuals construct additional models adding to the demands on working memory. If this were so older persons with their more limited memory resources might be expected to be especially impaired on three-model problems, and this was found not to be the case. The results are, however, consistent with the results of Evans et al. (1999), who maintain that individuals generally construct only a single model of the premises and fail to search for counter-examples or alternative models. As only a single model is constructed even for the more complex syllogisms, the demands on working memory will not vary by problem type, and an age by problem type interaction would not be expected.

Gilinsky and Judd (1994) sought to establish the extent to which the age deficits in syllogistic reasoning were moderated by working-memory differences. Salthouse (2000) argues that processing speed underpins adult age differences in working memory, and the present study included the standard measure of processing speed among the covariates. This did indeed reduce the age-related deficit in syllogistic reasoning to below statistical significance. Thus, whereas Gilinsky and Judd's more global measure of working memory failed in this respect, control for the age-related slow-down in information-processing speed did produce the expected result.

[3]This was the correlation for "abstract construction problems", which are equivalent to those used in the present study.

However, the situation was rendered less clear-cut when measures of the other aspects of working memory were included as covariates, most notably the word fluency measures. In relation to this development two aspects are particularly worthy of note. First, the magnitude of the residual age effect was increased to the point where it exceeded the effect generated by age as the sole explanatory variable. Second, the residual age effect again became statistically significant. How can this pattern of results be explained? There seems little doubt that some aspects of syllogistic reasoning do involve processes that are subject to age-related decline. The speed of information processing may relate to these aspects. On the other hand the fact that word fluency was associated with a suppressor effect in the context of explaining the age-related variance suggests that other processes perhaps less vulnerable to age-related decrements may at least in part underpin important aspects of syllogistic reasoning.

It is clear from Table 1 that many of the variables listed there, although significantly correlated with age, are not strongly related to syllogistic reasoning. In view of the observations set out in the previous paragraph, it might be reasonable, therefore, to consider whether or not syllogistic reasoning and working-memory performance, as it is represented in Table 1, tap different cognitive processes. In part this issue can be addressed with reference to the neuropsychological processes that underpin these two capacities. With this in mind, this paper now contrasts the neuroanatomical mechanisms underpinning syllogistic reasoning with those underpinning the various aspects of working-memory functioning.

Clearly syllogistic reasoning even in its abstract form is a complex task that relies on numerous cognitive capacities of which working memory is just one. These capacities are likely to be distributed in different cortical areas of the brain. Indeed neural imaging research has revealed that syllogistic reasoning with *abstract* content (as in the present study) is associated with increased activation in a variety of cortical locations. For example, the process of integrating the premises is associated with increased activation in dorsolateral prefrontal areas (BA6 bilateral, BA8 left hemisphere),[4] the left inferior prefrontal cortex (BA10 and BA44) and the right inferior/medial prefrontal cortex (BA46). In addition, bilateral non-frontal areas in the parietal cortex (BA7) and the occipital cortex (BA19) are also implicated. Relative to integrating the premises, the key aspect of syllogistic reasoning—that is, evaluating the conclusion, is associated with increased activation in the inferior frontal lobe (BA45 bilaterally, BA44 left hemisphere only), bilateral cerebellum and basal ganglia, bilateral fusiform gyrus (BA18), and the left superior parietal lobe (BA7: Goel, Buchel, Frith, & Dolan, 2000).

Other studies investigating deductive reasoning more generally have also revealed increased activation in various left hemisphere prefrontal cortical structures. For example, the left dorsal frontal gyrus (part of the dorsolateral prefrontal cortex; Osherson et al., 1998) and the left middle and inferior frontal gyri and the left cingulate gyrus (Goel, Gold, Kapur, & Houle, 1997, 1998). In addition, non-frontal areas were also implicated, including the cerebellum and the association occipital and parietal cortices.

Switching the focus now to working memory, a recent review of functional neuroimaging studies reveals that distinct working-memory functions appear to be centred on different neuroanatomical structures. Passive storage structures appear to be located in posterior brain

[4]BA denotes Brodmann Area.

areas including parietal and occipital structures. The active maintenance of information seems to implicate ventrolateral prefrontal areas whereas complex executive functions recruit the dorsolateral prefrontal cortex and the anterior cingulate cortex (Hartley & Speer, 2000; Jonides et al., 1998). Random number generation, which like random letter generation is believed to utilize executive working-memory processes, has also been found to rely on the left dorsolateral prefrontal cortex and the anterior cingulate cortex (Jahanshahi, Dirnberger, Fuller, & Frith, 2000). Some evidence is consistent with a left hemisphere focus for verbal working-memory tasks whereas the right hemisphere is implicated in spatial working-memory functioning (Smith & Jonides, 1998; Thomas et al., 1999). However other studies suggest a bilateral arrangement—for example, Clark et al. (2000) and Mottaghy et al. (2000) have shown that verbal working memory functions are served by bilateral dorsolateral prefrontal cortical areas as well as other non-frontal regions.

Thus it is apparent that syllogistic reasoning and working memory are served by similar cortical structures. However, whereas dorsolateral prefrontal areas feature prominently and bilaterally in accounts of working-memory functioning, especially with regard to the executive aspects, syllogistic reasoning, in particular the evaluation of conclusions, appears to rely more on left hemisphere ventrolateral and medial prefrontal regions as well as structures outside the neocortex. Indeed, Owen (2000) has proposed that the executive system is fractionated with different prefrontal regions responsible for executive functions depending on the exact nature of the task. More specifically, Owen argues that, depending on the specific requirements of the task, the executive component may utilize ventrolateral prefrontal regions, dorsolateral structures, or both areas working in collaboration. Thus to summarize, the less prominent role played by the dorsolateral prefrontal cortex in syllogistic reasoning might therefore account for the weak correlations between the working-memory measures and syllogistic reasoning performance.

Given this possible partial cortical dissociation between working memory and syllogistic reasoning it is perhaps not surprising that control for age differences in the various measures of working memory did little to attenuate the age-related decline in syllogistic reasoning performance. Most of the working-memory measures were significantly correlated with age, with older persons failing to match the scores achieved by their younger counterparts. Like the verbal and spatial working-memory tasks described earlier, most of those used in the present study have been shown to utilize dorsolateral prefrontal cortical (DLPFC) areas. For example, the visuo-spatial tasks are similar to those used by Postle, Berger, Taich, and D'Esposito (2000), which were associated with increased activation of the DLPFC. The random letter generation task is similar to the task employed by Jahanshahi et al. (2000), which again utilizes the DLPFC. The Wisconsin card-sorting test has also been found to be associated with increased activation in the right DLPFC (Lombardi et al., 1999), whereas another study revealed bilateral DLPFC increased activation (Berman et al., 1995). In addition, whereas simple span tasks probably do not substantially implicate DLPFC, it seems likely that reading span and computation span with their concurrent storage and processing requirements do utilize DLPFC structures (Jonides et al., 1998). Thus to summarize, most of the working-memory tasks set out in Table 1 that are subject to age-related declines appear to rely prominently on the DLPFC.

A possible implication is therefore that age-related changes in the DLPFC might be responsible for age-related declines in the aspects of working-memory performance included in the present study. Further, as it is less reliant on the DLPFC, utilizing instead other prefrontal and non-frontal areas, a substantial part of the age deficit observed in syllogistic reasoning may well be attributable to other mechanisms.

Interestingly, the two word fluency measures were not significantly correlated with age. This is consistent with results obtained elsewhere—for example, Parkin and Java (1999) and Capitani, Laiacona, and Basso (1998) failed to find age effects in word fluency performance. However, although not correlated with age, word fluency did register significant correlations with syllogistic reasoning. Furthermore, when introduced as a covariate, one of the word fluency measures acted as suppressor variable and actually accentuated the age-related impairment in syllogistic reasoning.

It might be reasonable to inquire what neuroanatomical aspects these two tasks have in common. Numerous studies have revealed that in addition to temporal and other non-frontal regions, the left-prefrontal areas are important in the performance of word fluency tasks (e.g., Elfgren & Risberg, 1998; Levin, Song, Ewing-Cobbs, Chapman, & Mendelsohn, 2001). However, there is less evidence that the DLPFC specifically is prominently involved. Whereas Stuss et al. (1998) found that left DLPFC lesions (but not right) impaired word fluency performance, Troyer, Moscovitch, Winocur, Alexander, and Stuss (1998) found that this only occurred when the task involved switching between letters or from category to category and that the number of words generated within a single category was unaffected. As the word fluency task used in the present study did not involve switching, it is unlikely to have been dependent on the DLPFC.

It was noted earlier that syllogistic reasoning was associated with increased activation of the bilateral basal ganglia (Goel et al., 2000). Interestingly, Parkinson's disease patients, who as part of their treatment received a left-sided pallidotomy (lesioning the globus pallidus, part of the basal ganglia), were substantially impaired in word fluency performance, whereas a range of other cognitive measures were less affected (Kubu, Grace, & Parrent, 2000). Thus, both the word fluency and syllogistic reasoning tasks used in the present study have in common the fact that they are both relatively dependent on left hemisphere frontal and non-frontal structures and relatively independent of the DLPFC. These factors distinguish them from the other working-memory measures included in the study and potentially make them less subject to age-related decline.

An implication of the arguments set out earlier is that age deficits in many aspects of cognitive functioning are related to age-related changes in the pre-frontal cortex and in particularly in the DLPFC. There is a growing volume of research evidence implicating the prefrontal cortex in cognitive ageing (see Langley & Madden, 2000, and West, 2000, for a review of the recent literature). More recently Phillips and Della Sala (1998) and Rypma and D'Esposito (2000) have asserted that age-related changes do not affect the prefrontal cortex in a uniform manner. Rather they argue that the age-related deterioration of the DLPFC is disproportionately responsible for the effects of cognitive ageing, with more ventrolateral areas, including the orbitoventral prefrontal cortex, less likely to be affected.

Although the neuropsychological research findings set out here are of considerable interest, it must be acknowledged that each of the observations made are based on the results of one or two studies involving small numbers of participants and using a range of relatively new methodologies. The results themselves and their usefulness in terms of providing a context for interpreting the outcomes of the present study must therefore be treated with some caution.

Thus to sum up, subject to the qualifications noted in the previous paragraph, the findings noted here and the results of the present study are consistent with an account of syllogistic reasoning[5] in terms of at least two broad processes that differ in the extent to which they are subject to age-related impairment. The evidence suggests that some aspects of syllogistic reasoning (e.g., processing the premises) may utilize the DLPFC. This structure is also implicated in a range of working-memory tasks, each of which is subject to pronounced age-related declines. On the other hand, other aspects of syllogistic reasoning (e.g., constructing conclusions) utilize other more ventral prefrontal regions and other non-frontal structures, which may be less subject to the effects of ageing. This interpretation, although inevitably somewhat speculative, at least goes some way towards accounting for the outcomes obtained in the present study.

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Original manuscript received 19 June 2001
Accepted revision received 18 October 2001

APPENDIX
Instructions to participants in syllogistic reasoning task

Much of human knowledge is cast with logical quantifiers such as all or some. Witness Lincoln's famous statement: "You can fool all of the people some of the time; you can even fool some of the people all of the time; but you can't fool all of the people all of the time." Our scientific laws are cast with such quantifiers also. It is important to understand how people reason with such quantifiers.

Most of the research on quantifiers in psychology has focused on a simple form of quantified deduction known as the categorical syllogism. Interest in this form dates back to the Ancient Greeks and much of Aristotle's writing on reasoning concerned the categorical syllogism.

Categorical syllogisms involve statements concerning the quantifiers some, all, no, and some not. Examples of such categorical statements are:

1. All doctors are rich.
2. Some lawyers are dishonest.
3. No politician is trustworthy.
4. Some actors are not handsome.

In experiments, the categories (e.g., doctors, rich people, lawyers, dishonest people) in such statements are frequently replaced by letters, say, A, B, C. This system serves as a handy shorthand for describing the material. In the tradition analysis of categorical statements, the foregoing sentences would be analysed into subject and predicate, the first category (e.g., doctor) being the subject and the second category (rich people) the predicate. Thus the statements might be rendered in this way:

1′. All A's are B's.
2′. Some C's are D's.
3′. No E's are F's.
4′. Some G's are not H's.

A categorical syllogism typically contains two premises and a conclusion. All three statements are of a categorical nature. The following is a simple example:

1. All A's are B's
All B's are C's
Therefore, All A's are C's

This syllogism, incidentally, is one that most people correctly recognise as valid. On the other hand, people accept with almost equal frequency the following invalid syllogism:

2. Some A's are B's
Some B's are C's
Therefore, Some A's are C's

(To see why this is invalid, consider replacing A with women, B with lawyers, and C with men.)

Some people find that it helps to represent syllogisms in a diagrammatic form. Diagram 1 illustrates the following syllogism: given that *all A are B* and *all B are C* then it follows that *all A are C*. (Everything inside the circle A is also inside the circle C.)

It might be tempting to conclude from the diagram that *some C are not A*. Clearly in Diagram 1 there are some members of C that are not contained within either A or B. However, it would be wrong to draw this conclusion because there is another way of drawing the diagram in which *all C are A* (see Diagram 2 in which the sets A, B, and C completely overlap with each other). Nevertheless, you can see that the conclusion *all A are C* follows from both diagrams and in fact which ever way you draw the diagram, provided that it satisfies the two initial premises then the conclusion *all A are C* will always be true.

Diagram 3 illustrates the syllogism: *some A are B* and *some B are C*. You can see from the diagram that it does not follow from this that *some A are C*. Clearly there are no points in A that are also within C since the two circles do not overlap. You might be tempted to conclude from this diagram that *no A are C*. However, it would be wrong to draw this conclusion because there is another way of drawing the diagram in which *some A are C* (see Diagram 4).

In general, before reaching a conclusion, you should see if there are any ways of representing the problem that are inconsistent with it. If it helps you may draw diagrams like the ones we have shown you but you need not do so and you are free to draw your conclusions by whatever means suits you.

Your task is to draw your own conclusions from each pair of the following premises so as to complete as many valid syllogisms as you can. In fact, no pair of premises is capable of generating more than two valid conclusions, most generate only 1, and for a few there are no valid conclusions that can be drawn. Be sure to base your judgement of every conclusion on whether or not it is necessarily implied by the stated premises, not on whether you believe it to be true or false based on your experience or previous knowledge.

Diagram 1

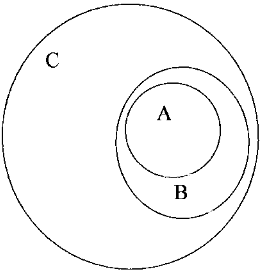

Diagram 2

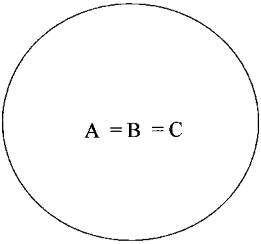

Diagram 3

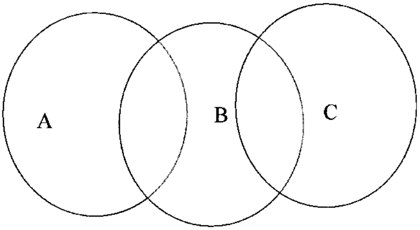

Diagram 4