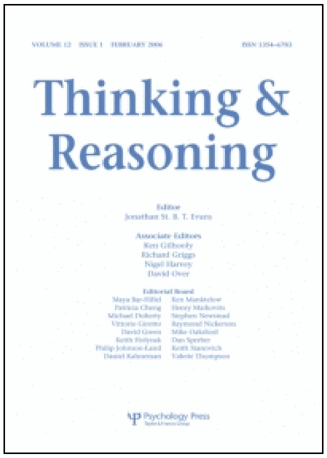

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Relational integration in older adults

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Relational integration in older adults

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Reasoning requires making inferences based on information gleaned from a set of relations. The relational complexity of a problem increases with the number of relations that must be considered simultaneously to make a correct inference. Previous work (Viskontas, Morrison, Holyoak, Hummel, & Knowlton, 2004) has shown that older adults have difficulty integrating multiple relations during analogical reasoning, especially when required to inhibit irrelevant information. We report two experiments that examined the ability to integrate multiple relations in younger, middle-aged, and older adults performing two other reasoning tasks. These tasks systematically varied relational complexity, and required either inductive reasoning (a version of the Raven's Matrices Task) or transitive inference. Our results show that as people age they have increasing difficulty in solving problems that require them to integrate multiple relations. This difficulty may stem from a decrease in working memory capacity.

Solving a problem using deductive or inductive reasoning depends on the ability to make correct inferences by integrating multiple relations. For example, if Sam is taller than Jane, and John is taller than Sam, one must integrate the two "taller than" relations in order to make the inference that John is taller than Jane. Deconstructing a reasoning task into the relations that must be integrated to make inferences provides a framework that makes it possible to define levels of relational complexity for that task. Halford (1998; Halford, Wilson, & Phillips, 1998) has suggested that the processing

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load for any step in a reasoning task can be determined by the number of relations (dimensions) that must be considered simultaneously in order to make the correct decision and continue on to the next step. Relations are viewed as analogous to degrees of freedom, or the number of independent sources of variation. At the lowest level of relational complexity (level 1), the reasoner needs to consider only one relation in order to solve the task correctly. At level 2, the reasoner must integrate two relations, and so on. For example, in the transitive inference problem described above, one must integrate two relations to infer that John is taller than Jane. If told that Sam is taller than Jane, Dan is taller than Eric, and Jane is taller than Dan, one would have to consider all three relations simultaneously in order to make the correct inference that Sam is taller than Eric (since the people mentioned in the first two premises do not overlap). This latter problem, then, would be considered a level 3 problem in terms of relational complexity.

Using the relational complexity framework, it is possible to investigate the processing demands of complex reasoning, and make more precise predictions as to how a breakdown in relational integration might be reflected in reasoning performance. While it is well established that reasoning ability declines with age (for reviews, see Salthouse, 1992, 2005), we have only begun to understand the mechanisms behind this decline. In the present study, we used transitive inference and inductive reasoning tasks to investigate the effects of age on the ability to integrate multiple relations. For both of the reasoning tasks used in the present study, we defined relational complexity as the number of relations one must simultaneously "hold in mind" in order to generate the solution.

Holding in mind multiple relations requires adequate "space" in working memory. This "space" is necessary both for temporary storage of items in short-term memory stores and for processing of items in working memory. Miller (1956) originally observed that the storage capacity of short-term memory is seven plus or minus two "chunks", or independent units of information. Since Miller's original observation, research has shown that most people are unable to process more than five chunks of information concurrently (Broadbent, 1975; Cowan, 2001; see also Fisher, 1984). The capacity of working memory, as defined by Baddeley and Hitch (1974) is also in this range.

In the model described by Baddeley and Hitch (1974), storage is distinctly separated from processing. Two slave systems, the visuo-spatial sketchpad, and the phonological loop, serve as the storage sites for limited amounts of modality-specific information. A third system, the central executive, manipulates the information from these two slave systems, supervises transfer into long-term memory, and coordinates appropriate actions. Recently, Baddeley (2000) introduced a fourth component, the limited-capacity episodic buffer, which holds information from several modalities using a multi-dimensional code during the time required by the central executive to bind that information into a cohesive episode and store it in long-term memory. In both of our tasks, participants have access to all of the information needed to make inferences at all times: thus, the demand on the "slave" storage systems is minimised and remains constant for each problem. As relational complexity in a problem increases, the central executive is increasingly engaged. The processing capacity of this component is taxed as the participant must manipulate the premises to arrive at the correct inference.

A considerable body of research documents a decline in working-memory capacity with age (Craik, Morris, & Gick, 1990; Dobbs & Rule, 1989). Most of the evidence supports the hypothesis that while primary or immediate memory processes, such as digit span, remain relatively constant throughout life, working-memory processes that involve manipulating information held in memory, and therefore the actions of the central executive, are vulnerable to age (Craik et al., 1990). There are several current theories of how working memory is affected by normal ageing. These theories posit limitations in storage capacity (see McCabe & Hartman, 2003), inability to inhibit irrelevant information (thereby placing unnecessary burdens on working memory; Hasher & Zacks, 1988), and reduced speed of processing (Salthouse, 1993). Craik and Byrd (1982) suggested that as adults age, they experience a decline in attentional resources. It is assumed that some tasks require more attentional resources in order to be performed successfully, while others are more automatic and require minimal attention. This hypothesis predicts that tasks that require more effortful processing, such as those with high demands on maintaining and manipulating several items in working memory, will be more difficult for older than for younger adults. Consistent with this hypothesis, ageing has been shown to impair problem solving in tasks such as the Tower of London (Phillips, Gilhooly, Logie, Della Sala, & Wynn, 2003), which require planning and place demands on working memory (for a review see Gilhooly, Phillips, Wynn, Logie, & Della Sala, 1999). Indeed, these results are consistent with the notion of a decline in the processing capability of the central executive, as it is the central executive that uses conscious awareness to bind information from the slave systems and episodic buffer with that in long-term memory (Baddeley, 2000).

Certainly, processes that depend on conscious awareness are most vulnerable to declines in attention. In reasoning tasks, Halford (1998) has argued that the relevant chunks of information are the relations that must be considered, and that the working memory capacity of humans is typically limited to four relations. Halford (1993) also found that young children can process fewer relations simultaneously than older children, demonstrating that the capacity of working memory in terms of relations increases with age. Does this capacity decline once an individual has reached a certain age?

In the present study we examined relational integration ability of younger, middle-aged, and older adults. Furthermore, we held visual and phonological complexity constant, and allowed our participants constant access to the necessary information, thereby increasing demands on working memory processing while holding demands on slave storage systems constant. If the declines observed with age result solely from a decrease in storage capacity, then any age-related deficits observed should be similar across all problems. If, however, processing abilities also decline with age, then our participants should experience the most difficulty with problems that require greater numbers of relations to be integrated.

In a previous study (Viskontas et al., 2004), we found that as people age, the ability to solve analogy problems at higher levels of relational complexity declines. In an analogical reasoning task, older adults had difficulty even at low levels of relational complexity, whereas middle-aged people were able to solve the problems accurately but took more time to do so. Our goal in the present study was to assess whether such deficits are specific to analogical reasoning, or extend to other types of reasoning as well.

In the present study, the performance of young, middle-aged, and older people was compared using two tasks that allow variations in level of relational complexity: a version of the Raven's Progressive Matrices task (Raven, 1941), which measures inductive reasoning, and a transitive inference task. We designed a version of the Raven's Progressive Matrices task that systematically increases the number of relations to be considered simultaneously (from one to four). The transitive inference task (i.e., Sam is taller than Jane, John is taller than Sam; therefore John is taller than Jane) requires successive integration of up to three relations. Both tasks manipulated relational complexity, defined as the number of relations that must be integrated to make correct inferences, while holding constant perceptual and other memory demands. In order to minimise short-term memory requirements, the premises were always perceptually available to the reasoners. Light, Zelinski, and Moore (1982) found that older adults did fail to integrate information across multiple premises even when the premises were remembered accurately. This study supports the notion that central executive processes are affected by age, and that age-related declines do not simply result from a storage capacity decrease. We predicted that older adults would be less able than their younger counterparts to integrate three or four relations. We also predicted that younger adults should be able to integrate three or fewer relations fairly easily, but even they will begin to have trouble integrating four relations, as this level of relational complexity taxes their processing capacity. This pattern is the one that we observed in our study of analogical reasoning across the lifespan (Viskontas et al., 2004).

We measured both response time and accuracy. Our basic prediction was that in our reasoning tasks, older participants would perform more poorly than younger participants on those problems that require the integration of multiple relations, but that they would perform similarly on questions that require processing of only one relation, as these problems place low demands on the central executive. We expected to find an interaction between age and level of relational complexity in each task for either accuracy, response times, or both dependent measures.

EXPERIMENT 1: INDUCTIVE REASONING

Experiment 1 compared inductive reasoning in younger, middle-aged, and older adults using a version of the Raven's Progressive Matrices task. This task was designed to systematically increase the number of relations to be considered simultaneously (one to four). This type of inductive reasoning involves hypothesis generation and testing: the reasoner is expected to make inferences about what conclusion the premises might allow, and to test these inferences until one is selected as satisfactory (see Sloman & Lagnado, 2005). While performing inductive reasoning, one must strategically bind relevant elements into specific roles to form new relational structures. This process requires working memory, specifically the central executive in Baddeley and Hitch's (1974) model. We designed our task in such a way that at higher levels of relational complexity, working memory requirements would increase as participants needed to form relations between more items and generate more complex hypotheses. We predicted that older participants would have particular difficulty with problems at higher levels of relational complexity, as these require greater working memory resources.

Method

Participants. Table 1 provides demographic information about the participants. There were 30 younger, 36 middle-aged, and 32 older participants. Middle-aged and some older participants were recruited using flyers posted in the medical plaza at the University of California, Los Angeles (UCLA) and other buildings on campus, and in senior recreation centres and libraries. The participants were paid $10 per hour for their participation. Younger participants were recruited through the UCLA Psychology Department. All were students at UCLA who were given course credit for participation in the study. All participants except three (one young, one middle-aged, and one older) were right-handed. None of the participants reported any history of neurological, psychiatric, or substance abuse problems.

TABLE 1
Demographic information about participants

		Age			Education	
Participants	*N*	*Mean*	*Range*	*% Women*	*Mean*	*SD*
Experiment 1 (RM)						
Young	30	19.8	17–6	67%	14.1	1.2
Middle-aged	36	49.4	40–5	64%	15.8	2.8
Older	32	74.9	66–6	56%	15.7	3.2
Experiment 2 (TI)						
Young	29	19.7	18–6	66%	14.3	1.3
Middle-aged	28	50.8	41–5	61%	15.8	2.5
Older	23	76.7	66–1	56%	15.2	3.6

Materials and procedure. Figure 1 provides examples of matrix problems at various levels of relational complexity. At the first level of relational complexity, reasoners need only consider one relation, as it changes the figures either across a row or down a column. At the second level of relational complexity, the figures change both across the row and down the column, so that participants must integrate two relations in order to solve the problem. Relational complexity continues to increase to the fourth level, in which the figures are changing in two ways across the row and in two ways down the column. There were six problems at each level of relational complexity.

The task was run on a laptop computer. A set of instructions prompted participants to first ‘‘form an image in your mind’’ of the figure that belongs in the empty box. When a participant had formed that image, they were to press the spacebar, at which point the alternatives appeared on the screen. The participant then pressed the one, two, three, four, five, or six key to indicate which alternative (among those in six boxes, labelled correspondingly) most closely matched their mental image. In order to distinguish between the time participants took to reason through the problem (‘‘mental image’’ response time) and the time the participants took to choose between the alternative (‘‘choose’’ response time), these two response times were recorded separately. Accuracy was measured using percent correct.

Results

Accuracy. Figure 2 presents mean accuracy of matrix completion across the various conditions. To ensure that the homogeneity of variance assumption was met, an arcsine transformation was performed on the proportion correct scores and these data were used in subsequent

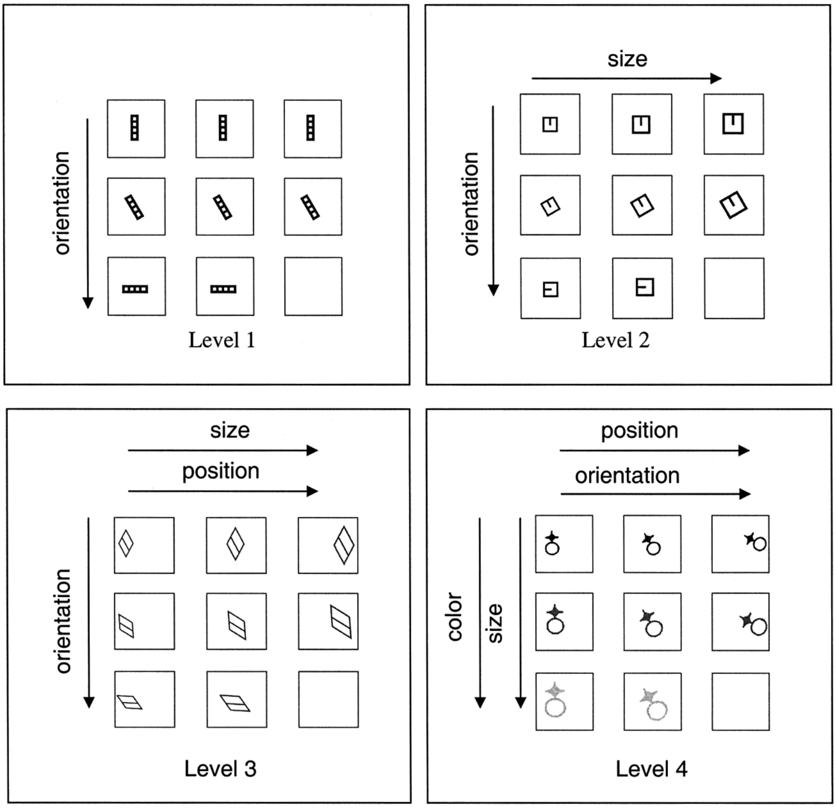

Figure 1. Example problems at each level of relational complexity from our version of the Raven's Progressive Matrices task. Participants examine how shapes change across the row and down the column, and decide which shape belongs in the bottom-right square.

analyses. An analysis of variance (ANOVA) was carried out on percent correct with age group as a between-subjects variable (older, middle-aged, and young) and level of relational complexity (i.e., number of relations that varied in the problem) as a within-subjects variable (1, 2, 3, and 4). This analysis revealed a significant main effect of age, $F(2, 95) = 12.29$, $p < .0001$, a significant main effect of level of relational complexity, $F(3, 285) = 70.04$, $p < .0001$, and a significant age $\times$ level interaction, $F(6, 285) = 2.47$, $p < .05$. A test of linearity revealed that the relational complexity effect had a strong linear component, $F(1, 95) = 234.01$, $p < .0001$. To test whether the effect of relational complexity was different for the various participant groups, we performed planned comparisons. Given that the participants were taking far more time to choose their answers at level 4, we only included levels 1, 2, and 3 in the planned comparison. Also, since the younger group was performing at ceiling on levels 1 and 2, we did not include their data in the analysis. Older adults showed a greater effect of relational complexity than did middle-aged adults, $F(2, 132) = 3.59$, $p < .05$.

Response time:"Mental image". The pattern of mean response times to form a mental image is depicted in Figure 3. An analogous ANOVA was carried out on response time to form a mental image. This analysis revealed a significant main effect of age, $F(2, 95) = 4.96$, $p < .01$, a significant main effect of level of relational complexity, $F(3, 285) = 22.58$, $p < .0001$, but no significant age $\times$ level interaction ($F < 1$). A test of linearity revealed that the relational complexity effect included a significant linear component, $F(1, 95) = 39.67$, $p < .0001$. Post hoc (Tukey's HSD) tests showed that older adults took more time to respond than younger adults, $p < .01$.

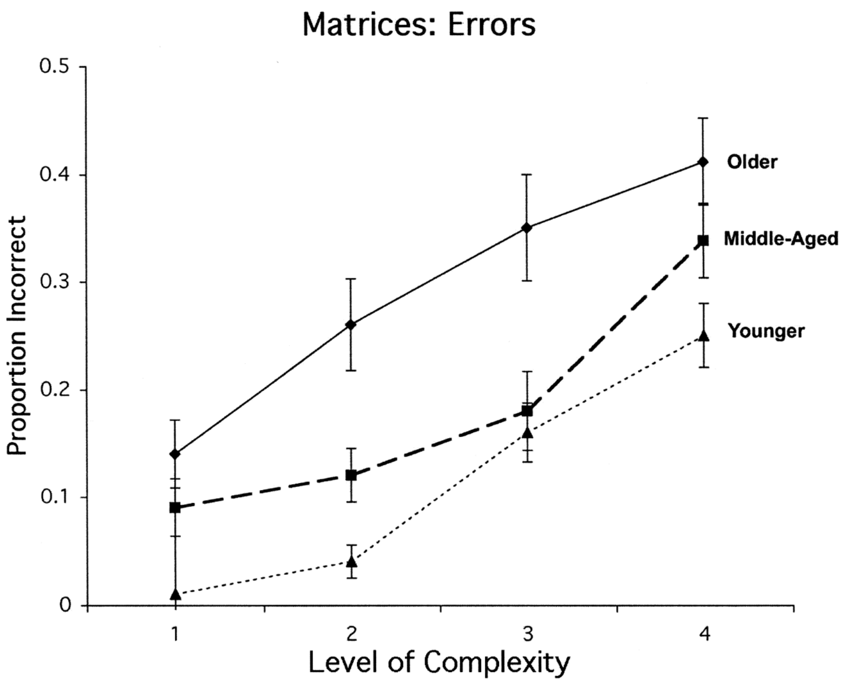

Figure 2. Errors made in the matrices task for younger ($n = 30$), middle-aged ($n = 36$), and older ($n = 32$) groups. Error bars depict standard error of the mean.

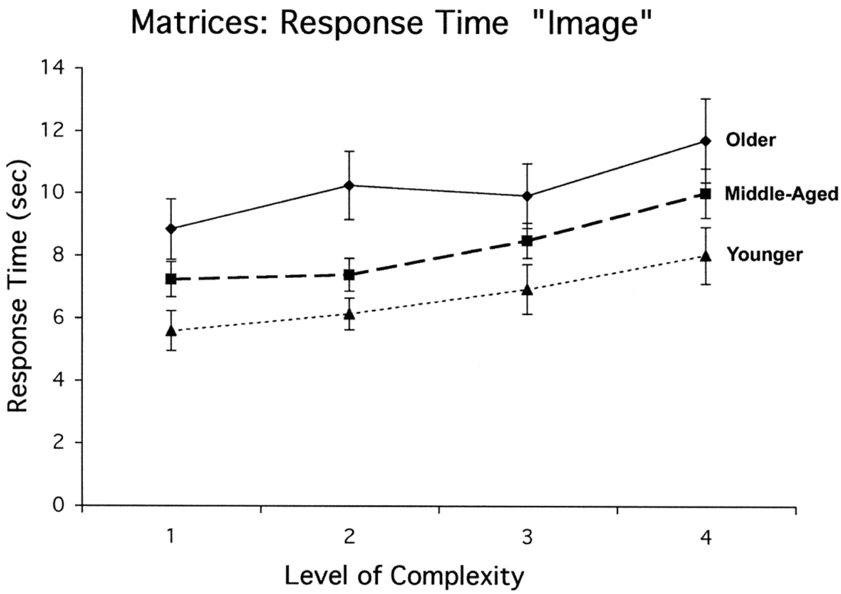

Figure 3. "Form a mental image" response time in the matrices task for younger (n = 30), middle-aged (n = 36), and older (n = 32) groups. Error bars depict standard error of the mean.

Response time: "Choose answer". Figure 4 depicts the pattern of mean response times to select the correct answer (correct trials only). An ANOVA revealed a significant main effect of age, $F(2, 95) = 30.80$, $p < .0001$, a significant main effect of level of relational complexity, $F(3, 285) = 41.25$, $p < .0001$, but no significant age $\times$ level interaction ($F < 1$). A test of linearity revealed that the relational complexity effect included a significant linear component, $F(1, 95) = 75.85$, $p < .0001$. Post hoc tests (Tukey's HSD) showed that younger adults made their choices significantly faster than did middle-aged adults ($p < .003$), who in turn chose significantly faster than did older adults ($p < .0001$); younger adults were also faster than older adults ($p < .0001$).

Proportion of total response time spent choosing an alternative. We also analysed the proportion of the total response time that participants spent "choosing" their answer. An ANOVA revealed a significant main effect of age, $F(2, 95) = 8.11$, $p < .001$, with proportions of 44%, 51%, and 59% for younger, middle-aged, and older participants, respectively. A significant main effect of level of relational complexity was also obtained, $F(3,$

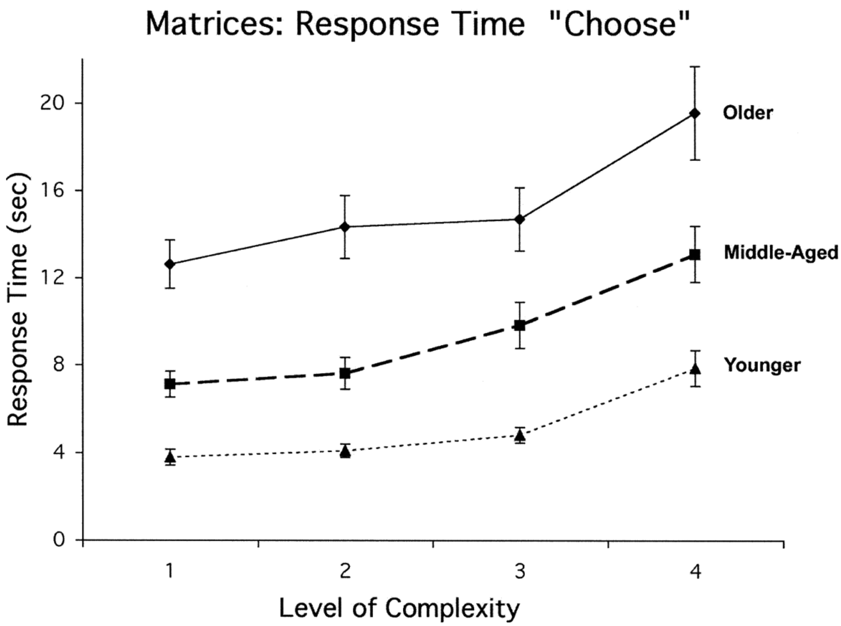

Figure 4. "Choose an alternative" response time in the matrices task for younger (n = 30), middle-aged (n = 36), and older (n = 32) groups. Error bars depict standard error of the mean.

285) = 10.40, $p < .001$, but no significant interaction ($F = 1.69$). Post-hoc tests (Tukey's HSD) revealed that older adults spent a greater proportion of their total time "choosing" from alternatives than did younger adults ($p < .0001$).

Discussion

All three groups showed progressively poorer performance as the number of relations that needed to be considered simultaneously increased, but only older participants showed particular difficulty at higher relational complexity levels. Although older participants did not commit more errors at level 4 than they did at level 3, this error-rate equality was likely due to a speed–accuracy trade-off, as the older participants were taking much more time to choose their answers at level 4 than at any other level. The interaction of age by relational complexity (levels 1–3) in accuracy suggests that as people age, they are increasingly affected by relational complexity. Since neither the general (or crystallised) knowledge needed for the task nor demands on "slave systems" change with relational complexity, it is reasonable to attribute this effect to increasing demands on working memory resources, especially those processes that rely on the central executive.

Interestingly, both middle-aged and younger groups took approximately the same amount of (or less) time to form a mental image of the answer than to actually choose from among alternatives. This result suggests that these groups were performing most of the reasoning process before they viewed the alternatives. In contrast, older people took longer to choose the answer than to form a mental image of it, suggesting that either their mental image was incorrect, or they were more distracted by the other alternatives. All three groups of participants showed an effect of level of relational complexity on the time it took them to choose the correct answer from a set of alternatives.

EXPERIMENT 2: TRANSITIVE INFERENCE

Experiment 2 compared the ability to make transitive inferences in younger, middle-aged, and older adults. In this task, all of the information necessary to make the conclusion is present in the premises. We chose the transitive inference task because it is possible to vary relational complexity, defined as the number of relational premises that must be considered together, simply by varying the order in which premises are presented (see Waltz et al., 1999). We predicted that older adults would have selectively greater difficulty in finding the solution at higher relational complexity levels.

Method

Participants. There were 29 younger, 28 middle-aged, and 23 older participants. Participants are characterised in Table 1. Some of these participants had already participated in Experiment 1.

Materials and procedure. Each transitive inference problem consisted of two to four propositions. There were 32 problems in total. The premises to be considered (e.g., John is taller than Jane) when solving a particular problem were exposed to participants constantly until they noted that they had finished that problem. The participant's task was to arrange cards, with names of the people in the premises (e.g., John, Jane) printed on them, in order from tallest to shortest, as deduced from the premises. At the first level of relational complexity, there was one problem with two premises (requiring three cards; e.g., "Dan is taller than Jane, Jane is taller than Abe" are the premises, Dan, Jane and Abe are the names on the cards), one with three premises (requiring four cards), and one with four premises (requiring five cards). At the second level of relational complexity, there was one problem with two premises, three problems with three premises, and six problems with four premises. At the 2 + level, there were five problems with four premises. At the highest level of relational complexity, level 3, there were two problems with three premises and eleven problems with four premises. Only the problems with four premises were included in the reported analyses, because these problems all required the same number of cards to be moved at each relational complexity level.

Each proposition was encased in a rectangle and included two names separated by the "taller than" relation. The task was to arrange the cards in order from tallest to shortest, from left to right along a flat surface. The cards were pre-ordered such that they followed the order of the names as they appeared on the page from left to right. This ordering was chosen to limit the variability of response times, as the participants did not have to search for each name. The problems were presented randomly in terms of level of relational complexity, but this random order was preserved for every participant. The first problem was treated as a practice trial and was not included in data analyses.

The problems were divided into four levels of relational complexity. At level 1, the correct answer could be determined by chaining together the relations, ordering the names in the same order in which they were introduced in the premises (e.g., John is taller than Sam, Sam is taller than Sean, Sean is taller than Jane, Jane is taller than Eric; see Waltz et al., 1999). At level 2, the correct answer required the consideration of two relations simultaneously in order to re-order the names (e.g., **Sam is taller than Sean**, Sean is taller than Jane, **John is taller than Sam**, Jane is taller than Eric, where relations in bold must be considered simultaneously). At level 2 + , participants had to consider two relations simultaneously followed by a second (separate) integration. An example would be **{Jane is taller than Eric, Sean is taller than Jane},** {John is taller than Sam, Sam is taller than Sean}. Here the first two premises must be integrated to re-order the three names; then the next two premises can be combined by simple chaining; and finally the two resulting partial orderings, {Sean, Jane, Eric}, {John, Sam, Sean}, must be integrated and re-ordered. Thus in level 2 + problems two successive integrations are required, but no single integration requires consideration of more than two premises. At level 3, participants had to consider three relations together to find the correct ordering, e.g., **Sean is taller than Jane, John is taller than Sam**, Jane is taller than Eric, **Sam is taller than Sean**. In such cases there is no overlap between the names in the first two premises, so integration has to be postponed until a third premise is presented to connect the first two.

Both accuracy (i.e., correct ordering) and time to complete the task were measured. To further examine the extent of relational integration, level 2 + and level 3 problems were chosen that required participants to move two cards simultaneously in order to solve the problem most quickly. For example, when solving this problem: **Sean is taller than Jane, John is taller than Sam**, Jane is taller than Eric, **Sam is taller than Sean**, the participant must remember that John is taller than Sam when moving the "Sam" card to indicate that Sam is taller than Sean—accordingly, the "John" and "Sam" cards must be moved together if all the relations are held in mind. The assumption underlying this measure is that if reasoners are holding both relations in mind, then they should move both cards, whereas if they are considering the relations serially, they should move one card at a time.

Results

Accuracy. The pattern of results for accuracy on transitive inference problems is depicted in Figure 5. An age (young, middle, old) × level of relational complexity (1, 2, 2 + , 3) ANOVA was conducted. This analysis revealed a significant main effect of age, $F(2, 77) = 10.02$, $p < .0001$, a significant main effect of level of relational complexity, $F(3, 231) = 37.05$, $p < .0001$, and a significant age × level interaction, $F(6, 231) = 7.24$,

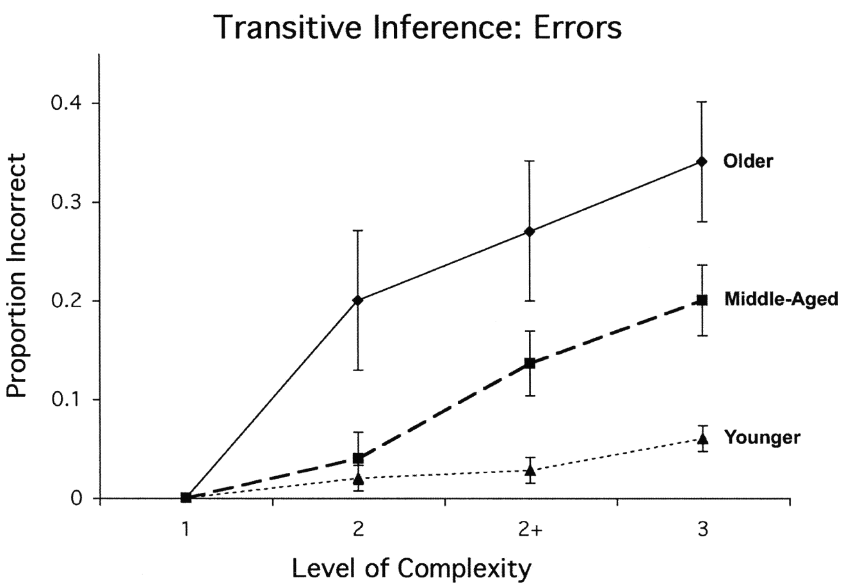

Figure 5. Errors made in the transitive inference task for younger ($n = 29$), middle-aged ($n = 28$), and older ($n = 23$) groups. Error bars depict standard error of the mean.

$p < .0001$. A test of linearity indicated that the relational complexity effect had a strong linear component, $F(1, 77) = 83.65$, $p < .0001$.

Since only two people made errors on two of the problems at the first level of relational complexity, creating a ceiling effect, an additional analysis that excluded the first level was also conducted. This analysis revealed a significant main effect of age, $F(2, 77) = 10.02$, $p < .0001$, a significant main effect of level of relational complexity, $F(2, 154) = 24.18$, $p < .0001$, and a significant age × level interaction, $F(4, 154) = 3.37$, $p < .05$. A test of linearity indicated that the relational complexity effect included a strong linear component, $F(1, 77) = 38.87$, $p < .0001$.

To test whether the effect of relational complexity differed across the various participant groups, we performed planned comparisons. The effect of relational complexity was not reliably different for middle-aged participants when compared to older adults, $F(2, 98) = 0.22$, $p = .80$. Older adults showed a greater effect of relational complexity than did young adults, $F(2, 100) = 4.10$, $p < .05$. Likewise, middle-aged adults also showed a greater effect of relational complexity than did younger adults, $F(2, 110) = 6.88$, $p < .01$.

Response time. Mean response times for the various conditions are shown in Figure 6. An age (young, middle, old) × level of relational complexity (1, 2, 2 + , 3) ANOVA revealed a significant main effect of age, $F(2, 77) = 14.05$, $p < .0001$, and a significant main effect of level of relational complexity, $F(3, 231) = 31.49$, $p < .0001$, but no significant age × level interaction, $F(6, 231) = 1.25$, $p = .28$. A test of linearity revealed that the effect of relational complexity included a linear component, $F(1, 77) = 57.47$, $p < .001$. Post hoc (Tukey's HSD) tests revealed that older adults took more time to complete the task than middle-aged adults ($p < .05$), and younger adults ($p < .001$), and middle-aged adults also took more time than younger adults ($p < .05$).

Card movement. Some of the questions at level 2 + and level 3 were designed so that the experimenter could infer the participant's reasoning processes from his or her movement of the name cards. In these trials, the critical final integration involved moving a *pair* of cards that the participant had already considered to a new location, based on the final premise. Failure to move the cards *together* was taken as evidence for a failure to maintain the relation between the cards in the pair when considering the new relation. In fact, this failure to move the cards together was the only systematic error that participants were observed to make. Table 2 shows the mean proportion of trials during which the cards were moved together. An age (young, middle, old) × level of relational complexity (2 + , 3) ANOVA conducted on the proportion of times the cards were moved correctly

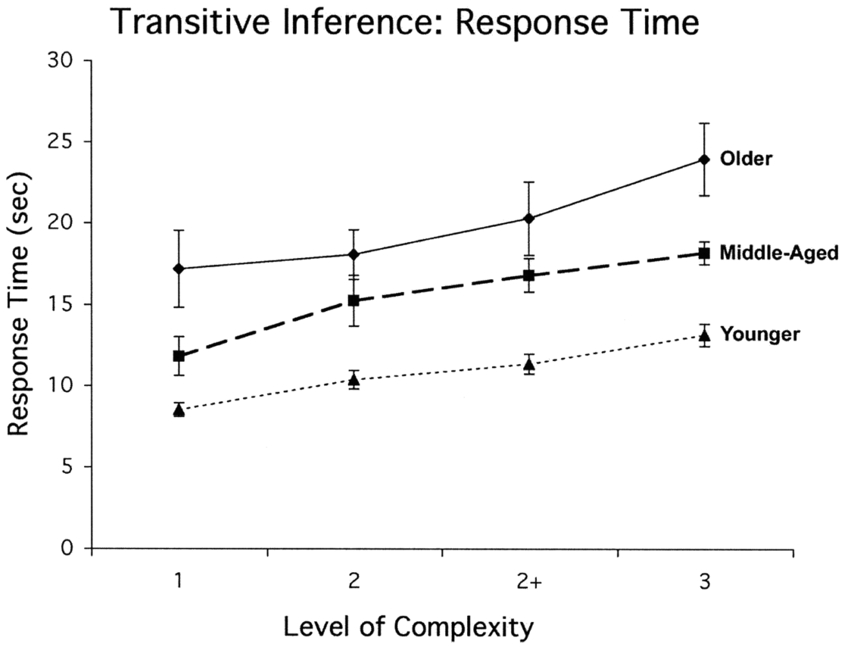

Figure 6. Response time in the transitive inference task for younger (n = 29), middle-aged (n = 28), and older (n = 23) groups. Error bars depict standard error of the mean.

TABLE 2
Mean proportion of trials in which cards were moved together

		Proportion moved together			
		Level 2 +		*Level 3*	
Participants	*N*	*Mean*	*SD*	*Mean*	*SD*
Young	29	.84	.22	.81	.20
Middle-Aged	25	.69	.26	.58	.22
Old	19	.57	.32	.52	.27

revealed a significant main effect of age, $F(2, 77) = 9.97$, $p < .0001$ and a significant main effect of level of relational complexity, $F(1, 77) = 14.45$, $p < .0001$. The age × level interaction was not reliable ($F < 1.5$). Post hoc tests (Tukey's HSD) indicated that older adults and middle-aged adults moved the cards incorrectly more often than did younger adults ($p < .0001$ and $p < .05$, respectively).

Discussion

Even when the lowest level of relational complexity is excluded from the analysis, a significant interaction of age and level of relational complexity was observed in accuracy of solving transitive inference problems. While middle-aged people performed much like younger people at level 2, their performance degraded to resemble older people's performance at level 2 + and level 3. Interestingly, the extra integration step in level 2 + was more difficult for middle-aged and older people than for younger people, who showed no difference in performance between levels 2 and 2 + , whereas even younger people found level 3 to be more difficult than lower levels. In terms of response time, on the other hand, none of the groups took significantly more time to complete items at level 2 + than those at level 2. Response time increased with relational complexity, and the trend towards an interaction suggests that older people required comparatively more time at the highest level of relational complexity than did either of the other two groups.

Finally, our card-laying observations indicated that older and middle-aged adults were less likely to move two cards simultaneously when relational integration was required. In contrast, younger adults could successfully manipulate those relations that they had already considered, and therefore they moved the two cards together when evaluating the third relation. Older and middle-aged adults are not as adept at maintaining previously considered relations when faced with new ones.

GENERAL DISCUSSION

Working memory and ageing

The results of the present study show that as people age they have increasing difficulty in solving reasoning problems that require them to integrate multiple relations. This impairment is evident in middle age and increases with advancing age. Analyses of performance on the matrices task (Experiment 1) revealed that older adults were differentially impaired at integrating multiple relations. Whereas young adults performed at ceiling at relational complexity levels 1 and 2, older adults made many errors at level 2 and performed close to chance at levels 3 and 4. The performance of middle-aged adults fell somewhere in between; this group performed slightly less well than young adults at relational complexity levels 2 and 3, and at a level comparable to that of the older adults at level 4. These results suggest that the decline in processing capacity in working memory follows a gradual pattern. Normal ageing does not produce an abrupt shift in the ability to process one versus multiple relations (the pattern observed for patients with extensive frontal lobe degeneration by Waltz et al., 1999). Furthermore, even when memory demands are minimised by the continual presence of the premises, normal ageing is accompanied by declines in processing capacity that cause impairments in relational integration.

With respect to the representation of information in working memory, our two tasks presumably tap different systems. In the matrices task, the information is primarily visual, whereas information in the transitive inference task is verbal. The fact that our older participants showed similar difficulties with each of the tasks also points to a more central processing deficit.

Interestingly, there was no difference among the age groups in the time required to form a mental image of the correct answer in the matrices task (Experiment 1). However, the groups did differ in the time required to choose the correct alternative. Younger people took more time only at the highest level of relational complexity, suggesting that in those trials they sometimes formed an incorrect mental image, so that their search time was compounded by further processing. The middle-aged adults showed this increase even at the third level, while the older adults took approximately the same amount of time at each level, suggesting that they were often correcting their images at all relational complexity levels, or were more distracted by the alternatives. This latter hypothesis is in keeping with the view that deficits in cognitive processing with age are due to failure of inhibition (Hasher & Zacks, 1988).

Analysis of performance on the transitive inference task (Experiment 2) indicated that older adults had difficulty in solving problems that required the integration of two or more relations, making more errors and taking more time to complete the trials. There was also a trend towards a difference between middle-aged and young adults in the amount of time required to solve the problems. Given that there was no response time difference at the first level of relational complexity, it is unlikely that simple motor slowing accounts for all the age differences in response times. In terms of accuracy, participants in all groups performed at ceiling at the first level of relational complexity. Moreover, even when only levels 2 and higher were considered, there was a significant interaction of age and relational complexity in terms of accuracy. It therefore appears that as people age, they are more susceptible to making errors at higher levels of relational complexity when performing transitive inference tasks.

In the transitive inference task, participants often made heuristic guesses about the placement of the cards described in the propositions that were presented first. The placement of cards in accordance with subsequent propositions required, in some cases, a re-evaluation of these initial guesses. This re-evaluation often required moving two cards simultaneously. Older adults tended not to re-evaluate their guesses correctly. Indeed, both middle-aged and older groups made significantly more re-evaluation errors, as manifested by failure to move two cards together, than did the younger group. In addition, when younger adults made errors, these were almost exclusively failures to re-evaluate correctly. Central to both of these reasoning tasks is the need to maintain and manipulate relational representations in working memory, a demand that increases with higher levels of relational complexity.

According to the Learning and Inference with Schemas and Analogies model of relational reasoning (LISA; Hummel & Holyoak, 1997, 2003), reasoning makes use of working memory to (1) orchestrate the precise firing of structural representations and (2) learn new correspondences between representational elements. In order to perform the first of these functions, LISA uses inhibition to select items for placement into working memory and to control the spreading of activation (i.e., the disambiguation of which elements of the recipient correspond to the active units in the driver). In a previous study (Viskontas et al., 2004), we were able to model the impairments in analogical reasoning seen in middle-aged and older adults by decreasing the effectiveness of attention and inhibition in working memory as modelled by LISA.

The process of relational integration may be thought of as analogous to the binding of multi-modal information into an episode. Information from several different premises must be manipulated and integrated, and a new inference must be generated. How the brain accomplishes binding is currently a hotly debated issue in cognitive neuroscience. In a particularly comprehensive review, Newman and Grace (1999) describe synchrony in neural firing as a strong candidate. In fact, the authors suggest that the brain distinguishes binding of items over differing time spans, achieving different goals, by reading distinct frequencies of oscillations. For example, these authors review evidence that sensory systems may use 40-Hz oscillations to bind elements into a coherent percept. Binding across a time frame of seconds, however, which is required in working memory, may rely on oscillations in the theta band (4–8Hz in rodents and possibly 7–9Hz in primates), as these oscillations characterise the activity of hippocampus and fronto-striatal circuits thought to underlie memory function. These and related observations may eventually provide a comprehensive model of the neural basis of working memory processes.

Overall, the patterns of decline in reasoning abilities with age that we observed in the present study and our previous study (Viskontas et al., 2004) are consistent with a large body of evidence suggesting that adult working memory efficiency decreases with age. While it remains unclear exactly what neurological changes cause age-related declines in working memory, some studies have shown that functional degeneration of the prefrontal cortex is a likely candidate (for a review see Raz, 2000). Since this same region has been implicated in working memory (for review, see Fletcher & Henson, 2001) and in relational reasoning (Robin & Holyoak, 1995), it is plausible that changes in the prefrontal cortex are responsible for the deficits found in older people. Our group has recently shown that patients with frontal lobe degeneration show profound deficits in relational integration in reasoning tasks similar to those used here (Morrison et al., 2004; Waltz et al., 1999). Gilhooly et al. (1999) reviewed a range of evidence indicating that cognitive deficits in ageing are attributable to degeneration of the dorsolateral prefrontal cortex. The present findings are consistent with the hypothesis that this brain area is critical in coping with relational complexity, and that age-related changes in frontal functioning are associated with reduced ability to reason about problems that require integration of multiple relations.

Future directions

Future studies may involve finer manipulations of the reasoning processes studied here in order to understand more completely how ageing affects performance. For instance, in the matrices task, the increase in reaction time for older adults during response selection may have been due to an increased effect of distraction from alternative answers, or it may reflect a degraded mental image of the subject's answer. By manipulating the delay between when the mental image is formed and when the choices appear, it may be possible to identify the source of the increased reaction time in older adults.

Another set of future studies could examine more precisely what aspects of working memory are engaged during different stages of reasoning and to investigate whether these processes interact with age. By presenting a secondary task designed to interfere with visuo-spatial, phonological, or central executive processes, it should be possible to identify the contributions of different storage and processing systems to relational integration in different tasks. To investigate the hypothesis that limits in attentional resources may interrupt relational integration in older adults, future research could include manipulations of distractors and the timing of their presentation. For example, during the matrices task, one could systematically vary the number and similarity of alternatives on a particular dimension. These manipulations would provide valuable insights into the contribution of working memory processes to reasoning in general and how working memory changes with age.

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