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Relational Integration, Inhibition, and Analogical Reasoning in Older Adults

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The difficulty of reasoning tasks depends on their relational complexity, which increases with the number of relations that must be considered simultaneously to make an inference, and on the number of irrelevant items that must be inhibited. The authors examined the ability of younger and older adults to integrate multiple relations and inhibit irrelevant stimuli. Young adults performed well at all but the highest level of relational complexity, whereas older adults performed poorly even at a medium level of relational complexity, especially when irrelevant information was presented. Simulations based on a neurocomputational model of analogical reasoning, Learning and Inference with Schemas and Analogies (LISA), suggest that the observed decline in reasoning performance may be explained by a decline in attention and inhibitory functions in older adults.

Human reasoning depends in part on the ability to integrate multiple relations and inhibit irrelevant information. For example, if Bill is taller than Carl and Abe is taller than Bill, one must integrate the two "taller than" relations to make the inference that Abe is taller than Carl. A relational analysis of reasoning provides a framework that makes it possible to define levels of complexity for particular reasoning tasks. According to Halford (1998; Halford & Wilson, 1980; Halford, Wilson, & Phillips, 1998), the processing load for any step in a task is determined by the number of dimensions, or relations, that must be processed simultaneously to make the decisions required for that step. Dimensions are viewed as analogous to degrees of freedom, or the number of independent sources of variation. At the first level of complexity (Level 1), the reasoner needs to consider only one relation to solve the task correctly.[1] At Level 2, the reasoner must integrate two relations, and so on. For example, it is necessary to integrate two relations to correctly solve the transitive inference problem described previously.

More generally, we define relational complexity as the number of relations that a reasoner must simultaneously "hold in mind" to generate the solution. This framework makes it possible to study the processing demands of complex reasoning and to better characterize changes in reasoning ability that occur during normal aging. Although it is known that reasoning ability declines with age (for reviews, see Salthouse, 1992a, 2005), the underlying mechanisms of this decline are not well established. In the current study, we investigate the effects of age on the ability to solve a complex analogical reasoning problem and consider possible algorithmic reasons for the observed decline with age.

The ability to hold in mind multiple relations relies on working memory capacity. (See Morrison, 2005, for a review of the role of working memory in reasoning.) Miller (1956) originally postulated that the processing capacity of what is now called working memory is seven plus or minus two "chunks," which are independent units of information. This estimate has since been reduced to between three and five chunks because 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). This lower estimate is more in keeping with the capacity of working memory as defined by Baddeley and Hitch (1974; Baddeley, 1996).

Halford (1998) identifies chunks with relations and argues that the working memory capacity of humans is typically limited to four relations. (See Halford, 2005, for a full review of the implications of these limitations for reasoning.) In a series of studies, Halford (1993) found that the number of relations that a child can process simultaneously increases with age. In the current study, we examined the course of relational integration ability at the other end of the developmental spectrum, comparing young, middle-aged, and older adults. It is possible that as individuals age, the ability to integrate multiple relations declines, such that older adults are less able to integrate three or four relations than their

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[1] For current purposes, we describe a taxonomy based on the number of relations definable as two-place predicates, such as taller-than (*A*, *B*). Halford's analysis includes lower levels of complexity, at which decisions are based on attributes (one-place predicates, such as red [*A*]) or on features that lack a predicate-argument structure (see Halford et al., 1998).

younger counterparts. We 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 because this level of complexity taxes their processing capacity. In older adults, we predicted relational integration deficits at lower levels of complexity.

The prediction of age-related decline in relational reasoning follows from the well-documented decline in working memory with aging (cf. Craik, Morris, & Gick, 1990; Dobbs & Rule, 1989). Most of the evidence supports the hypothesis that whereas primary or immediate memory processes, such as digit span, remain relatively constant throughout life, working memory processes that involve manipulating information held in memory are vulnerable to age (Craik et al., 1990). Three major theories of why working memory may be especially vulnerable have received considerable attention in the literature. Salthouse (1993) has postulated that the speed at which items can be processed in memory undergoes a steady decline with age once an adult has reached maturity. This theory predicts that older adults should take more time to complete working memory tasks and that those tasks that require much sequential processing should be impaired as participants essentially run out of processing time. In support of this hypothesis, Salthouse and colleagues have shown that aging leads to poorer reasoning performance as the number of premises that must be encoded and remembered increases (Salthouse, 1992b; Salthouse, Legg, Palmon, & Mitchell, 1990; Salthouse, Mitchell, Skovronek, & Babcock, 1989). These studies did not, however, find evidence that relational complexity (defined as the number of premises relevant to the inference) effects interacted with age. These studies used sequential presentation of premises, so any effect of complexity may have been swamped because of forgetting of the earlier premises by older participants. Light, Zelinski, and Moore (1982) have found that older adults fail to integrate information across multiple premises even when the premises were remembered accurately. In the current study, all premise information is continuously displayed, minimizing the need for short-term storage of premises.

A second theory, proposed by Craik and Byrd (1982), suggests that with age, adults experience a decline in attentional resources. It is assumed that some tasks require more attentional resources in order to be performed successfully, whereas others are more automatic and require minimal attention. This theory 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.

Hasher and Zacks (1988) proposed a third theory also related to the attentional account. They proposed that as people age, they have difficulty inhibiting irrelevant stimuli and are more subject to interference effects. This theory predicts that as problems are made more complex by the addition of irrelevant information, older adults will experience more trouble maintaining enough focus to complete the task (cf. Mayr, 2001). Supporting this theory are findings by May, Hasher, and Kane (1999) that suggest that older people are more susceptible to proactive interference (PI) than younger adults in tasks that assess working memory span. The role of inhibition in reasoning is consistent with Baddeley's (1996) characterization of the functions of the executive component of working memory, which includes the capacity to attend selectively to a stimulus while inhibiting the disrupting effects of others. Moreover, inhibitory control may be closely linked to the ability to reason with multiple relations. Robin and Holyoak (1995) argued that responses based on complex relations require inhibition of competing responses based on individual elements used to form the relations.

We hypothesize that the capacity to make inferences based on relations will depend on inhibitory mechanisms that allow one to selectively attend to relevant relations while suppressing other relations and features of stimuli that are not relevant to the target inference. Often it is necessary to select a correct inference from close foils (either physically presented or self-generated as possible alternative inferences) and act on the basis of the correct inference while avoiding alternative responses. If Hasher and Zacks (1988) are correct in proposing that inhibitory control declines with age, then older people will have particular difficulty in problems with salient distractors that must be inhibited in the course of reasoning. This hypothesis is consistent with evidence that older adults exhibit larger belief-bias effects in syllogistic reasoning (Gilinsky & Judd, 1994); that is, they are less able to judge logical validity of arguments independently of their prior knowledge about the truth of the premises and conclusion.

In the current study, the performance of young, middle-aged, and older people was compared on the People Pieces Analogy task (Sternberg, 1977). This task was adapted by Morrison (2001) to systematically vary the number of relations and the need for inhibition of irrelevant information while maintaining a constant level of visual complexity. We measured both response time and accuracy. Our basic prediction was that older participants would perform more poorly than younger participants on the problems that require the integration of multiple relations but would perform similarly on questions that require the processing of only one relation. Because participants have freedom to move along the speed–accuracy trade-off function, we did not expect to necessarily find an interaction for both response times and accuracy; however, we expected to find an interaction between age and level of relational complexity for at least one of the two dependent measures. Furthermore, we report simulation results that illustrate how the effects of aging on reasoning can be understood within a neurocomputational model that integrates the attentional and inhibition accounts of aging (Hummel & Holyoak, 1997, 2003).

Sternberg's (1977) People Pieces Analogy task, like other analogy tasks, requires mapping the relational structure in one situation onto another situation. In our version of the task, each term of the four-term analogy problem consisted of a cartoon character that possessed one value on each of four binary traits (clothing color, gender, height, and width). Participants were asked to compare the relationship of these traits between two pairs of characters. They were asked to attend to one to four of the traits and were instructed to ignore the other traits. If any of the to-be-attended-to relations were different across the pairs, participants were to respond "different," and if all of the to-be-attended-to relations were the same they were to respond "same." This version of the task improves on Sternberg's original task by deconfounding the relational complexity of the task with the visual complexity of the stimuli. In each problem, the four cartoon characters are different from each other regardless of the number of traits to be attended to. In addition, this set of materials allowed manipulation of distraction as well as relational complexity. We predicted that older adults would have more trouble performing increasingly complex analogical reasoning, based on both relational complexity and need for inhibition, than middle-aged or younger adults.

Method

Participants

There were 31 younger, 36 middle-aged, and 27 older participants. Participants are characterized in Table 1. Middle-aged and some older participants were recruited by using flyers posted in the medical plaza at the University of California, Los Angeles (UCLA) and other buildings on campus and in senior recreation centers and libraries. The participants were paid $10/hr for their participation. Younger participants were recruited through the UCLA Psychology Department. All were students at UCLA and were given course credit for participation in the study. All participants except 3 (1 young, 1 middle-aged, and 1 older) were right-handed. None of the participants reported any history of neurological, psychiatric, or substance abuse problems when explicitly questioned by the experimenter.

A subset of 14 older participants performed a battery of standardized executive function tasks on a separate session. As shown in Table 2, these participants performed well within age-appropriate norms on each of these tasks.[2]

Materials and Procedure

In the People Pieces Analogy task, participants were presented drawings of four cartoon characters on a computer screen (Figure 1). Each character had one of two characteristics on each of four traits: gender (male or female), height (short or tall), width (wide or narrow), and clothing color (black or white). Thus, each pair of cartoon characters possessed four relations, one for each of the traits. Participants were to judge whether the relations for the pair of cartoon characters on the left were the same or different as the relations for the cartoon characters on the right.

Relational complexity. Participants were cued to attend to from one to four of the relations. For example, in the problem shown in Figure 1A, the participants were to attend to gender and color. The two characters on the left were different with respect to gender, as were the two characters on the right, making the relation between the pairs the same. Likewise, the two characters on the left were the same with respect to color as were the two characters on the right, also making the relation between the pairs the same.

Distraction. There were also trials in which there were one or two unattended traits that displayed a relation inconsistent with that of the attended traits. These distracting relations were presented at Levels 1 and 2 of relational complexity and involved either one or two of the unattended traits. For example, in the problem shown in Figure 1B, the participants were to attend to color (Complexity Level 1) while ignoring the other traits. In this problem, two of the to-be-ignored traits (i.e., height and width) had relations that were different across the pairs (i.e., the two characters on the left were the same height, whereas the two characters on the right were different height; the two characters on the left were different width, and the two characters on the right were same). Thus, participants would need to inhibit information from these traits to solve the problem correctly. If participants were asked to attend to color and gender for this trial, the analogy would still be true because both pairs share the same relations with respect to these attributes (same for color, different for gender). The participant would still have to ignore the height and width relations because, for the pair on the left, both characters have the same height but different width, whereas the characters forming the pair on the left have different heights but the same width: Attending to either of these attributes would lead to a decision that this is a false analogy.

Different trials. Different problems were created by making one attended relation from the left pair not match one relation from the right pair. For example, in the problem shown in Figure 1C, the participant is to attend to three traits in which the relation for one of the traits (i.e., height) is not the same between the two pairs of characters. Thus, the correct answer for this problem is "different."

The traits to be attended to appeared before the characters and remained visible during problem solving so as to not confound short-term memory for the trait with the relational complexity of the problem. When participants were ready to solve the problem, they pressed the space bar to see the cartoon characters, and then they pressed one button for "same" and another button for "different." There were 112 problems in total. There were 64 *same* problems and 48 *different* problems in the testing set. In the *same* problems, there were 8 problems at each level of complexity (i.e., 1–4) with no unattended distracting relations. In addition, for complexity Levels 1 and 2, there were 8 problems with one unattended distracting relation and 8 problems with two unattended distracting relations. In the different problems, participants were asked to attend to from one to four traits, and in each case one relation was different. Three sample problems from each level of complexity were presented to the participants before the task began, with feedback concerning the accuracy of their decision. Participants who were unclear about the procedures or who performed poorly during the practice were given the instructions again verbally and visually and then were given additional practice until they indicated they understood the sample problems.

Table 1
Demographic Information for Participants

No. participants	Mean age (years)	Range	% Women	Education (years)	
				M	*SD*
Young, 31	19.8	17–26	65	14.2	1.3
Middle-aged, 36	49.9	38–62	64	15.9	2.6
Older, 27	75.1	66–86	52	15.9	2.9

Results

Relational Complexity: Accuracy

The pattern of accuracy in solving the analogy problems is depicted in Figure 2. Because the participants were required to make a choice between two responses, d' values were calculated and used in the analyses. An Age (young, middle, old) × Level of Complexity (number of attributes to attend to [1, 2, 3, 4]) analysis of variance (ANOVA) revealed a significant main effect of age group, $F(2, 91) = 14.10$, $MSE = 4.77$, $p < .01$ ($\eta^2 = .237$), a significant main effect of level of complexity, $F(3, 273) = 21.02$, $MSE = 0.189$, $p < .01$, ($\eta^2 = .188$), but no significant Age Group × Level interaction, $F(6, 273) = 0.598$, $MSE = 0.189$, $p < .73$. A test of linearity indicated that the main effect of relational complexity included a linear trend, $F(1, 91) = 37.09$, $p < .01$. Post

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[2] Characterizing data were obtained in a second session subsequent to the analogy task. There could be a concern, therefore, that the subset of older participants who returned for the second session possessed higher cognitive ability than those who did not. However, a post hoc analysis revealed no evidence that participants with characterizing data performed the analogy task more quickly or accurately than those who lacked characterizing data. In fact, in the only cell that showed a difference, the characterized group performed more slowly than the noncharacterized group. Thus, if anything, there is reason to think the characterizing data we obtained underestimates the cognitive abilities of the group as a whole.

Table 2
Characterizing Information on a Subset of the Oldest Participants

Older group subset ($n = 14$)	Age (years)	Education	*MMSE*[a]	Stroop Interference *t* score[b]	CTT Int. score[c]	Fluency: FAS[d]	Fluency: animals[e]
M	74.2[f]	16.3	29.3	48.2	1.20	45.5	18.9
SEM	1.3	0.82	0.30	1.6	0.26	4.1	1.3

[a] MMSE = Mini-Mental State Exam; cutoff for dementia is 24.
[b] Stroop Interference score: normative data from Golden (1978): $M = 50$, $SD = 10$).
[c] Color Trails Test Interference score: normative data from D'Elia et al. (1994) for adults aged 60–74 with an education of 16 years: $M = 1.18$, $SD = 0.58$; for adults aged 75–89 with 16 years of education: $M = 1.09$, SD = 0.63.
[d] Phonemic Verbal Fluency (FAS): normative data from Tombaugh, Kozak, and Rees (1999) for adults aged 60–79, with an education of 13–21 years: $M = 42.0$, $SEM = 0.89$.
[e] Semantic Verbal Fluency (animals): normative data from Tombaugh et al. (1999) for adults aged 70–79, with an education of 13–21 years: $M = 18.2$, $SEM = 0.43$.
[f] Range = 68–80.

hoc tests (Tukey's honestly significant difference [HSD]) indicated that there were significant differences in accuracy between younger and older adults ($p < .01$) and between middle-aged and older adults ($p < .01$). This increase in errors in older participants was comparable for problems in which the relationship within each pair was same or different ($F < 1$). Thus, it did not seem to be the case that there was a different pattern of errors for older and younger participants.

Relational Complexity: Response Time

The pattern of mean correct response time results is depicted in Figure 3A. Five older participants were excluded from this analysis because they had a score of 0 in accuracy at one or more of the levels. An ANOVA revealed a significant main effect of age group, $F(2, 86) = 16.42$, $MSE = 33.87$, $p < .01$ ($\eta^2 = .276$), a significant main effect of level of complexity, $F(3, 258) = 134.80$, $MSE = 3.74$, $p < .01$ ($\eta^2 = .611$) , and a significant Age Group × Level interaction, $F(6, 258) = 3.09$, $MSE = 3.74$, $p < .01$ ($\eta^2 = .067$). A test of linearity indicated that the main effect of relational complexity included a linear trend, $F(1, 86) = 274.37$, $p < .01$. To test whether the effect of complexity was different for the various participant groups, we performed planned comparisons. The effect of complexity was reliably different for middle-aged participants when compared with young adults, $F(3, 195) = 7.22$, $MSE = 2.13$, $p < .01$ ($\eta^2 = .100$). Likewise, older adults also showed a greater effect of complexity than did young adults, $F(3, 153) = 4.20$, $MSE = 4.08$, $p < .01$ ($\eta^2 = .076$) . Older adults, however, did not show a greater effect of complexity than middle-aged adults, $F(3, 168) = .389$, $MSE = 5.31$, $p = .76$.

Relational Complexity: Item Analysis

To ensure that each attribute was equally difficult to attend to, we performed an Age (young, middle, old) × Attribute (color, gender, width, height) ANOVA for trials at Level 1, when there were no attributes to inhibit. In accuracy, we found no significant main effect of attribute ($F < 1$) and no significant interaction with age ($F < 1$). Not surprisingly, we did find a significant main effect of age, $F(2, 91) = 16.79$, $p < .01$. The same pattern was found in response time: with no significant main effect of attribute, $F(3, 228) = 1.72$, $p = .17$, no significant interaction ($F < 1$), and a significant main effect of age, $F(2, 76) = 4.69$, $p < .05$.

Inhibition: Accuracy

The pattern of accuracy in solving the analogy problems at different levels of inhibition is depicted in Figure 4A and B. Because the participants were required to make a choice between two responses, d' values were calculated and used in the analyses. An Age (young, middle, old) × Level of Complexity (number of attributes to attend to [1, 2]) × Number of Suppressed Attributes (0, 1, 2) ANOVA revealed significant main effects of age group, $F(2, 91) = 12.61$, $MSE = 6.91$, $p < .01$ ($\eta^2 = .217$), and level of complexity, $F(1, 91) = 10.56$, $MSE = .242$, $p < .01$ ($\eta^2 = .104$), a significant Age Group × Level interaction, $F(2, 91) = 3.17$, $MSE = .242$ $p < .05$ ($\eta^2 = .065$), and a significant main effect of number of items to suppress, $F(2, 182) = 5.56$, $MSE = 087$, $p < .01$ ($\eta^2 = .058$), and no other significant main effects or interactions. A test of linearity indicated that the main effect of relational complexity included a linear trend, $F(1, 91) = 10.56$, $p < .01$, as did the main effect of number of items to be suppressed, $F(1, 91) = 5.23$, $p < .05$. Post hoc tests (Tukey's HSD) indicated that there were significant differences in accuracy between younger and older adults ($p < .01$) and between middle-aged and older adults ($p < .01$).

Inhibition: Response Time

The pattern of mean correct response time results is depicted in Figure 5A and C. Four older participants were excluded from this analysis because they had a score of 0 in accuracy at one or more of the levels. An ANOVA revealed significant main effects of age group, $F(2, 87) = 17.04$, $MSE = 44.04$, $p < .01$ ($\eta^2 = .291$), and level of complexity, $F(1, 87) = 142.69$, $MSE = 5.49$, $p < .01$ ($\eta^2 = .625$), a significant Age Group × Level of Complexity interaction, $F(2, 87) = 4.64$, $MSE = 5.49$, $p < .05$ ($\eta^2 = .107$), a significant main effect of number of items to be suppressed (inhibition), $F(2, 174) = 24.98$, $MSE = 2.48$, $p < .01$ ($\eta^2 = .223$), a significant Age Group × Inhibition interaction, $F(4, 174) = 3.98$, $MSE = 2.48$, $p < .01$ ($\eta^2 = .087$), a significant Level of Complexity × Inhibition interaction, $F(2, 174) = 10.20$, $MSE = 3.07$,

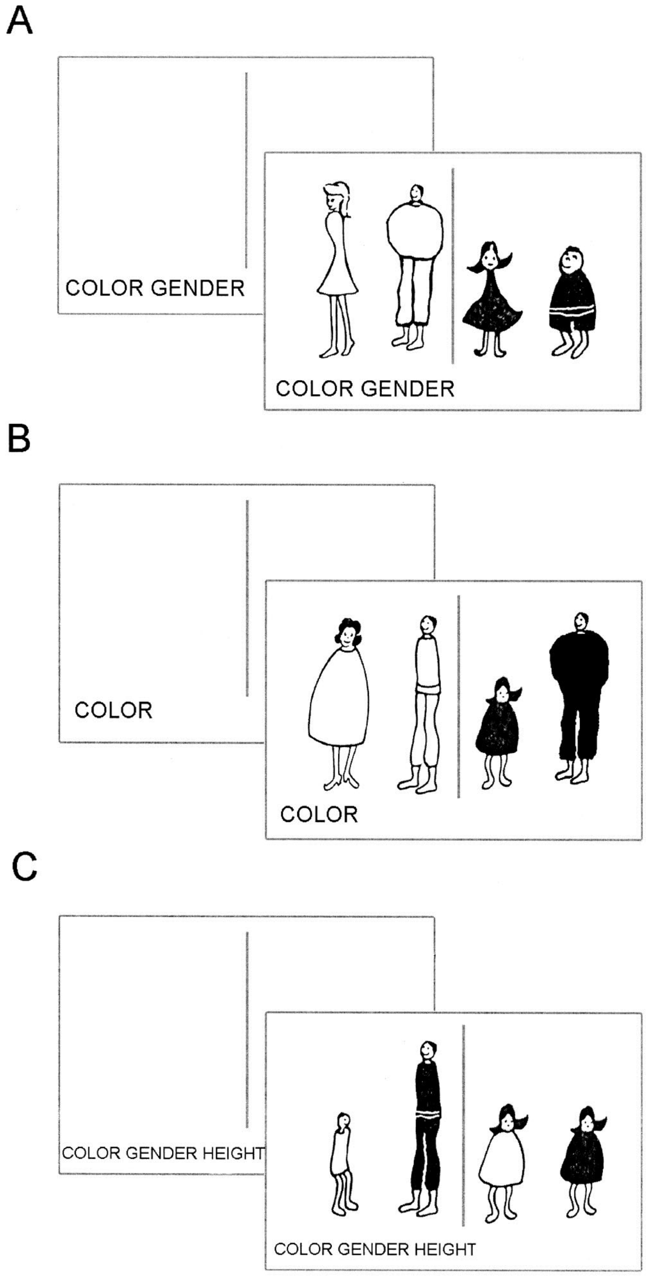

Figure 1. Example problem from the People Pieces Analogy Task. A: two relations, none to ignore (inhibit); B: one relation to attend to, two to ignore (inhibit); C: different problem.

$p < .01$ ($\eta^2 = .107$), and finally a significant Age Group × Level of Complexity × Inhibition interaction, $F(4, 174) = 2.54$, $MSE = 3.07$, $p < .05$ ($\eta^2 = .059$). A test of linearity indicated that the main effect of relational complexity included a linear trend, $F(1, 87) = 142.69$, $p < .01$, as did the main effect of inhibition, $F(1, 87) = 38.70$, $p < .01$. To test whether the effects of complexity and inhibition were different for the various participant groups, we performed planned comparisons. The Age Group × Level of Complexity × Inhibition interaction was not significant for middle-aged versus older adults ($F < 1$), but it was significant for older versus younger adults, $F(2, 104) = 5.08$, $MSE = 2.25$, $p < .01$ ($\eta^2 = .089$), and also for middle-aged versus younger adults, $F(2, 130) = 4.54$, $MSE = 2.43$, $p < .05$ ($\eta^2 = .065$).

Simulation of People Pieces Analogy Task in Learning and Inference With Schemas and Analogies

In an effort to understand the nature of the effect of age on performance on the People Pieces Analogy task, we modeled the aging results using Learning and Inference with Schemas and Analogies (LISA; Hummel & Holyoak, 1997, 2003), a neurally plausible symbolic-connectionist model of analogical reasoning. Although numerous computational models of analogy have been developed (see French, 2002; Holyoak, 2005, for reviews), no other such model has been used to simulate aging data. LISA was designed to model analogical reasoning, has intrinsic working memory constraints resulting from its architecture, and has also been used to simulate the effects of frontal and temporal degeneration on analogical reasoning (Morrison et al., 2004).

LISA represents propositions using a hierarchy of distributed and localist units (see Figures 6 and 7 for a schematic representation of LISA's architecture and Hummel & Holyoak, 1997, 2003, for a more complete description of the model's architecture and operation). At the bottom of the hierarchy, semantic units represent objects and relational roles in a distributed fashion. For example, a person might be represented by semantic features corresponding to the following properties: person, male, ~female (where "~" indicates negation), wide, ~narrow, tall, ~short, White, and ~Black; similarly, each role of the relation same-height (person1, person2) is represented by semantic features corresponding to relation, same, same-height, and ~different-height. The relations used in the current simulations, such as same-gender (x, y), same-width (x, y), different-gender (x, y), all happen to be symmetrical, meaning that r (x, y) implies r (y, x). The semantic representation of the first role of such a relation is, therefore, identical to that of the second. In the case of asymmetrical relations, such as loves (x, y) or gives (x, y, z), the different roles of a relation will have nonidentical semantic representations (see Hummel & Holyoak, 1997, 2003, for examples). The resulting distributed representations make explicit what different people have in common and

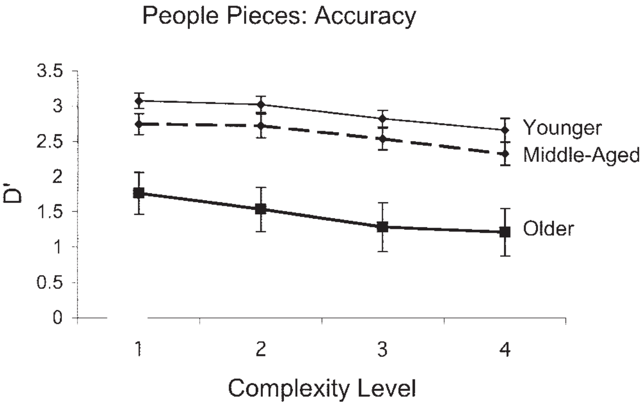

Figure 2. The d' values in the People Pieces Analogy task for younger (n = 31), middle-aged (n = 36), and older (n = 27) groups. Error bars depict standard errors of the mean.

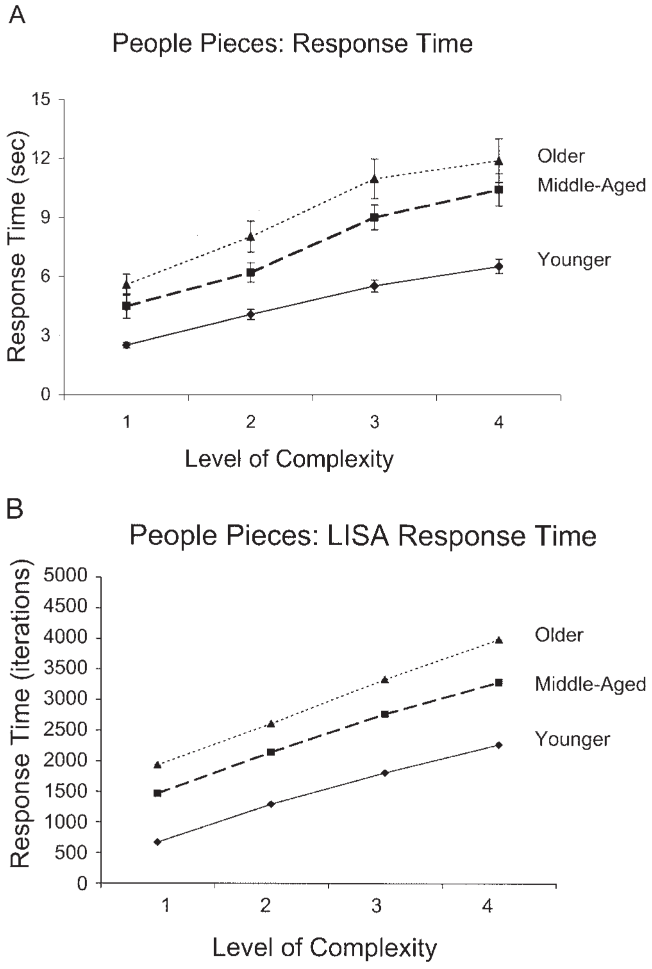

Figure 3. Response time in the People Pieces Analogy task (a) for younger (n = 31), middle-aged (n = 36), and older (n = 22) groups (error bars depict standard error of the mean) and (b) response times based on learning and inference with schemas and analogies (LISA) simulations.

how they differ and what different relations have in common and how they differ.

Predicate units represent relational roles in a localist fashion and have bidirectional excitatory and inhibitory connections to the corresponding semantic units (e.g., the predicate unit for the first role of same-height has bidirectional excitatory connections to all the semantic units representing that role, such as same and same-height, and bidirectional inhibitory connections to all the negated features of that role, such as different-height). Object units are just like predicate units, except that they are connected to semantic units describing things rather than roles (e.g., Person1 might be connected to person, male, ~female, and Black to trait, color, and Black). Subproposition (SP) units bind roles to their arguments and have bidirectional connections to the corresponding predicate and object units. In the case of different color (Black, White), one SP would bind Black to different-color1 (the predicate unit representing the first role of the different-color relation) and another would bind White to different-color2. At the top of the hierarchy, proposition (P) units bind role-filler bindings into complete propositions via excitatory connections to the corresponding SPs (see Figure 6). A complete analog (which, in the case of the current simulations, is a description of pair of characters) is represented by the collection of semantic, predicate, object, SP, and P units that collectively code the propositions in that analog (see Figure 7). Separate analogs do not share object, predicate, SP, or P units. However, all analogs are connected to the same set of semantic units. The semantic units thus permit the units in one analog to communicate with the units in another.

When a proposition is activated (i.e., placed in working memory), the binding of its roles to their arguments is represented by synchrony of firing: All the units under a given SP (i.e., a role-filler binding, represented by an SP, a predicate unit, an object unit, and their associated semantics) fire in temporal synchrony with one another, and separate SPs fire out of synchrony with one another (see Hummel & Holyoak, 1992, 1997). The effect on the semantic units is a set of mutually desynchronized patterns of activation, one pattern for each SP (i.e., role-filler binding). In the case of different (Black, White), the semantic features of Black would fire in synchrony with the features of different-color1, whereas White would fire in synchrony with different-color2.

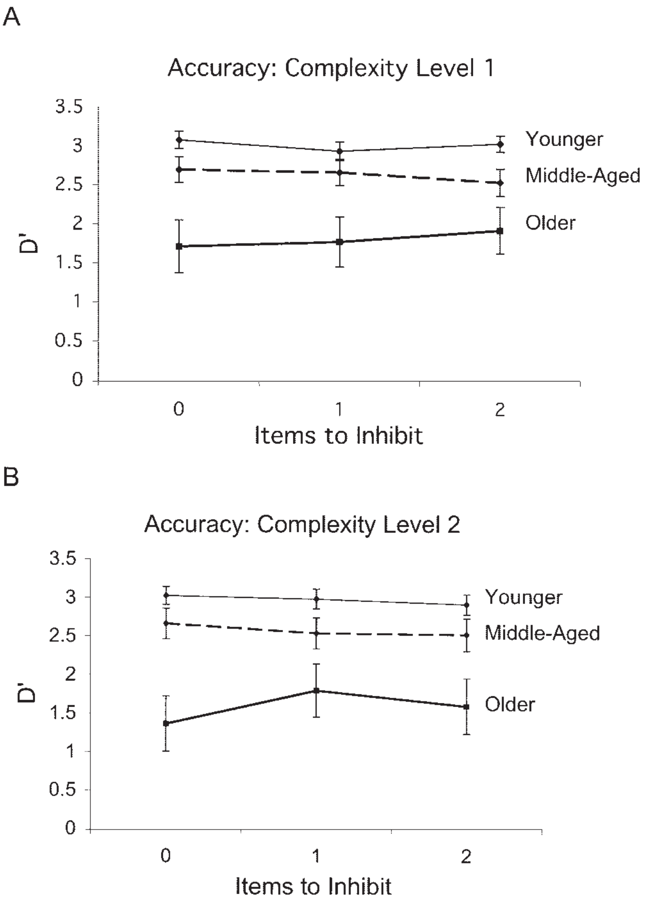

Figure 4. The d' values in the People Pieces Analogy task at (A) first level of complexity and (B) second level of complexity and three levels of inhibition for younger (n = 31), middle-aged (n = 36), and older (n = 27) groups. Error bars depict standard errors of the mean.

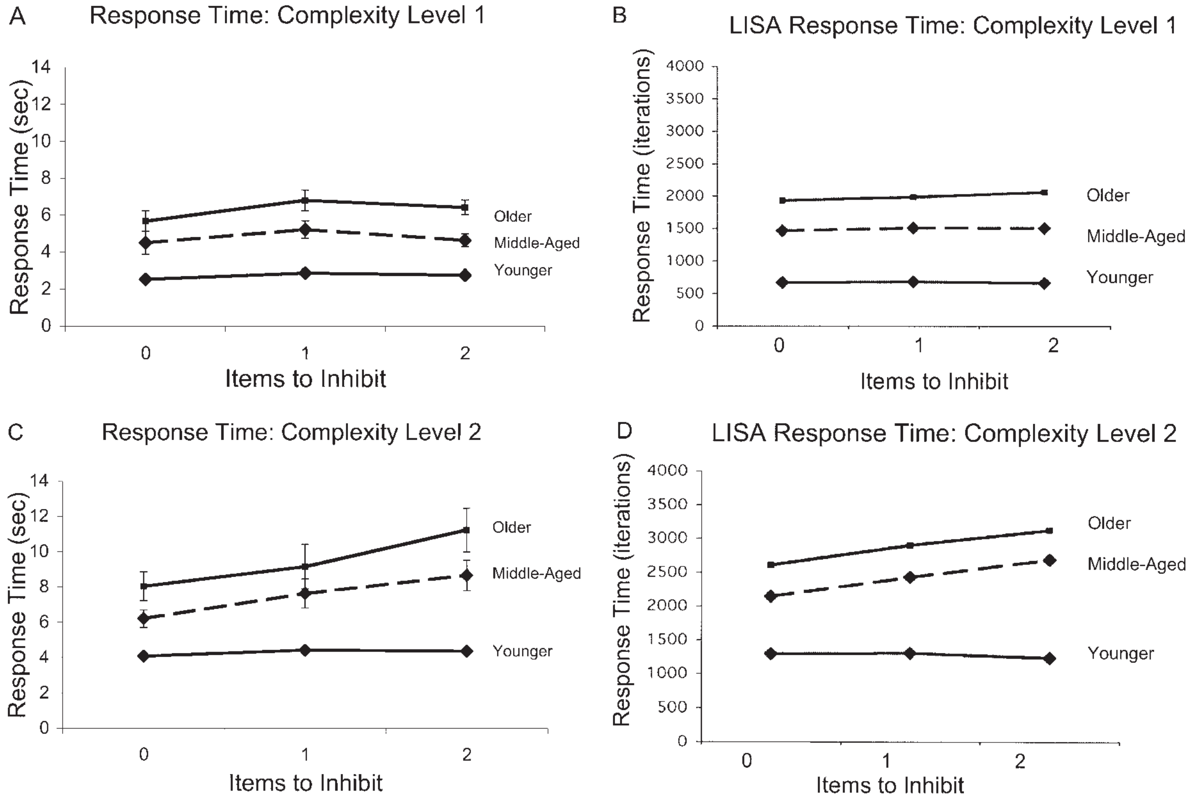

Figure 5. A: Response time in the People Pieces Analogy task for three levels of inhibition at first level of complexity for younger (n = 31), middle-aged (n = 36), and older (n = 23) groups; B: corresponding learning and inference with schemas and analogies (LISA) simulations; C: human data for second level of complexity; and D: corresponding LISA simulations. Error bars depict standard errors of the mean.

The final component of the LISA architecture is a set of mapping connections between units of the same type (e.g., object, predicate) in separate analogs. These connections grow whenever the corresponding units are active simultaneously and thereby permit LISA to learn the correspondences between structures in separate analogs. They also permit correspondences learned early in mapping to influence the correspondences learned later. For the purposes of memory retrieval, analogical mapping (Hummel & Holyoak, 1997), analogical inference, and schema induction (Hummel & Holyoak, 2003), analogs are divided into two mutually exclusive sets: a driver and one or more recipients. Processing is controlled by the driver: One (or at most three) at a time, propositions in the driver are placed into working memory (i.e., activated) and allowed to fire their SPs (along with their object and predicate units); as noted previously, all the SPs in working memory fire out of synchrony with one another. The resulting patterns of activation on the semantic units drive the activation of propositions in the recipient analogs and serve as the basis for analogical mapping, inference, schema induction, and all the other functions LISA performs. This representation, based on synchrony for role-filler binding, provides a natural account of the capacity limits of working memory because it is only possible to have a finite number of bindings simultaneously active and mutually out of synchrony (see Appendix A in Hummel & Holyoak, 2003, for a detailed treatment of the working memory capacity limits in LISA).

In LISA, inhibition is critical to the selection of information for processing in working memory. Specifically, inhibition plays a central role in (a) LISA's working memory capacity, (b) its ability to select items for placement into working memory, (c) its ability to control the spreading of activation in the recipient (i.e., its ability to disambiguate which elements of the recipient correspond to the active units in the driver), and (d) its ability to use intermapping-connection competition to enforce structural constraints on the discovery of analogical mappings (such as the 1:1 mapping constraint; Holyoak & Thagard, 1989).

Inhibition plays a key role in LISA's working memory capacity (property a) because the capacity of LISA's working memory is equal to the number of role-filler bindings (corresponding to SPs in the driver) that LISA can keep simultaneously active and mutually out of synchrony with one another. Inhibitory competition between SPs is what allows multiple SPs to fire out of synchrony: If this inhibition is reduced, then the number of SPs that can fire cleanly out of synchrony with one another declines; and when multiple SPs fire at the same time, the resulting superposition of role-filler bindings on the semantic units fails to specify which roles are bound to which fillers (see Hummel & Holyoak, 2003, Appendix A).

Inhibition plays a role in the selection of items to enter working memory (Property b) because selection is a competitive process: Propositions in the driver compete to be entered into working memory on the basis of several factors, including their pragmatic centrality or importance (Spellman & Holyoak, 1996), support

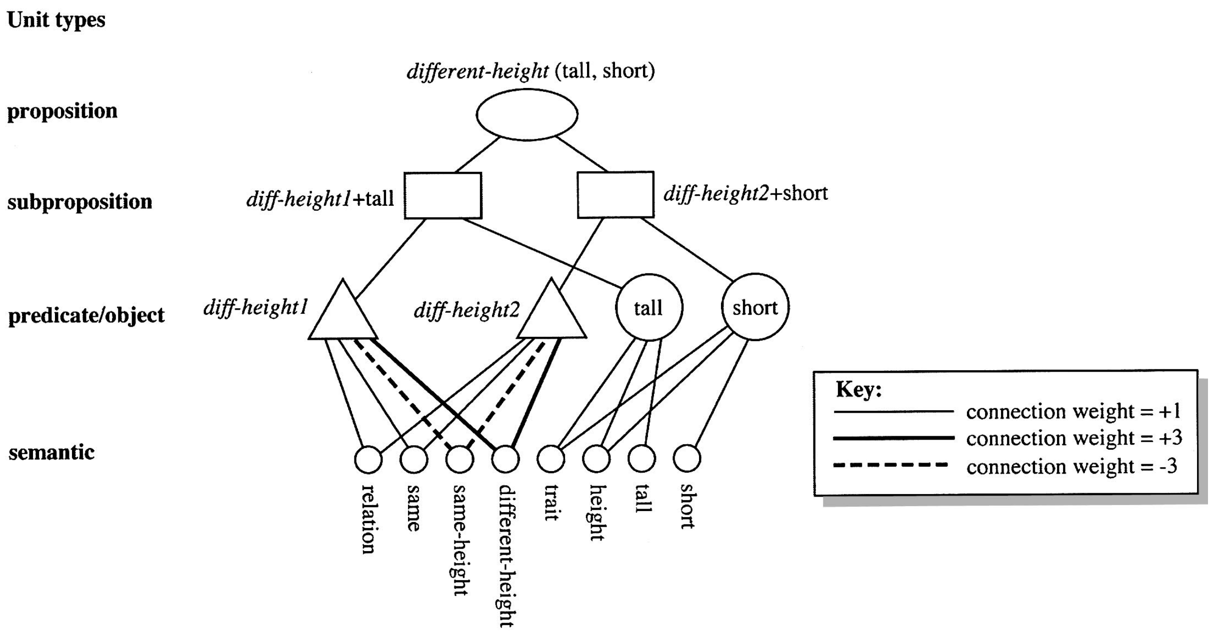

Figure 6. Learning and inference with schemas and analogies representation of the proposition different (diff)-height (tall, short).

from other propositions that have recently fired, and the recency with which they themselves have fired. Reduced inhibition results in reduced competition and more random selection of propositions to fire. The selection of which propositions are chosen to fire, and in what order, can have substantial effects on LISA's ability to find a structurally consistent mapping between analogs (Kubose, Holyoak, & Hummel, 2002). It follows that reduced inhibition, resulting in more random selection of propositions into working memory, can likewise affect LISA's ability to discover a structurally consistent mapping.

The role of inhibition in the activity of a recipient analog (property c) is directly analogous to its role in the activity in the driver. Inhibition causes units in the recipient to compete to respond to the semantic patterns generated by activity in the driver. If LISA's capacity to inhibit units in the recipient is compromised, then the result is a loss of competition, with many units in the recipient responding to any given pattern generated by the driver. The resulting chaos hampers (in the limit, completely destroys) LISA's ability to discover which units in the recipient map to which in the driver.

Finally, inhibition plays a crucial role in the competitive interactions between connections representing inconsistent mappings (e.g., mappings from a single unit in the driver to two or more units in the recipient; see Hummel & Holyoak, 1997, 2003). As a result, reduced inhibition can impair LISA's ability to find a structurally consistent mapping between the driver and recipient by reducing this competition between inconsistent mappings (property d).

To model the People Pieces Analogy task in LISA, we made several assumptions. First, although the participants are cued to only attend to certain traits in each problem, we represented the entire relational structure of a problem in LISA. This assumption is consistent with results reported by Morrison (2001), who found that unattended traits do influence People Pieces Analogy performance. To instruct LISA regarding which traits are to be attended to, we coded the relevant traits with higher importance values (Hummel & Holyoak, 1997). As noted previously, the likelihood that LISA will choose a proposition in the driver to enter working memory is proportional to the importance of that proposition. The effect of importance on probability of entering working memory is moderated by the strength of inhibition (i.e., the greater the inhibition, the greater is the influence of importance on probability of entering working memory).

To simulate aging in LISA, we investigated the role of attentional and inhibitory processes by (a) decreasing the role of importance (which we assume to correspond to whether a trait is to be attended vs. unattended) on the probability that a proposition is chosen to enter working memory and (b) decreasing the strength of inhibitory connections in both the driver and recipient. Both of these changes are controlled by the inhibition parameter. We simulated younger, middle-aged, and older participant performance by setting this parameter at values of 1.0, 0.7, and 0.6, respectively.

Figure 3B shows the influence of these changes. In Figure 3B, decreases in the inhibition parameter result in increases in LISA's response times (i.e., the number of iterations necessary for LISA to settle) across problems at all four levels of complexity. These increases show a slight interaction with complexity (consistent with the behavioral results; see Figure 3A). Figure 5 (B and D) reveals that LISA simulations of response time also show a three-way interaction among age, relational complexity, and the number of traits to be ignored (also consistent with the behavioral results; see Figure 3A and C). The model accounts for 96% of the variance in the mean response times for the various conditions across the three age groups. In summary, the results of the LISA simulations suggest that decreases in the efficiency of selective attention and the effectiveness of inhibition in working memory may explain the

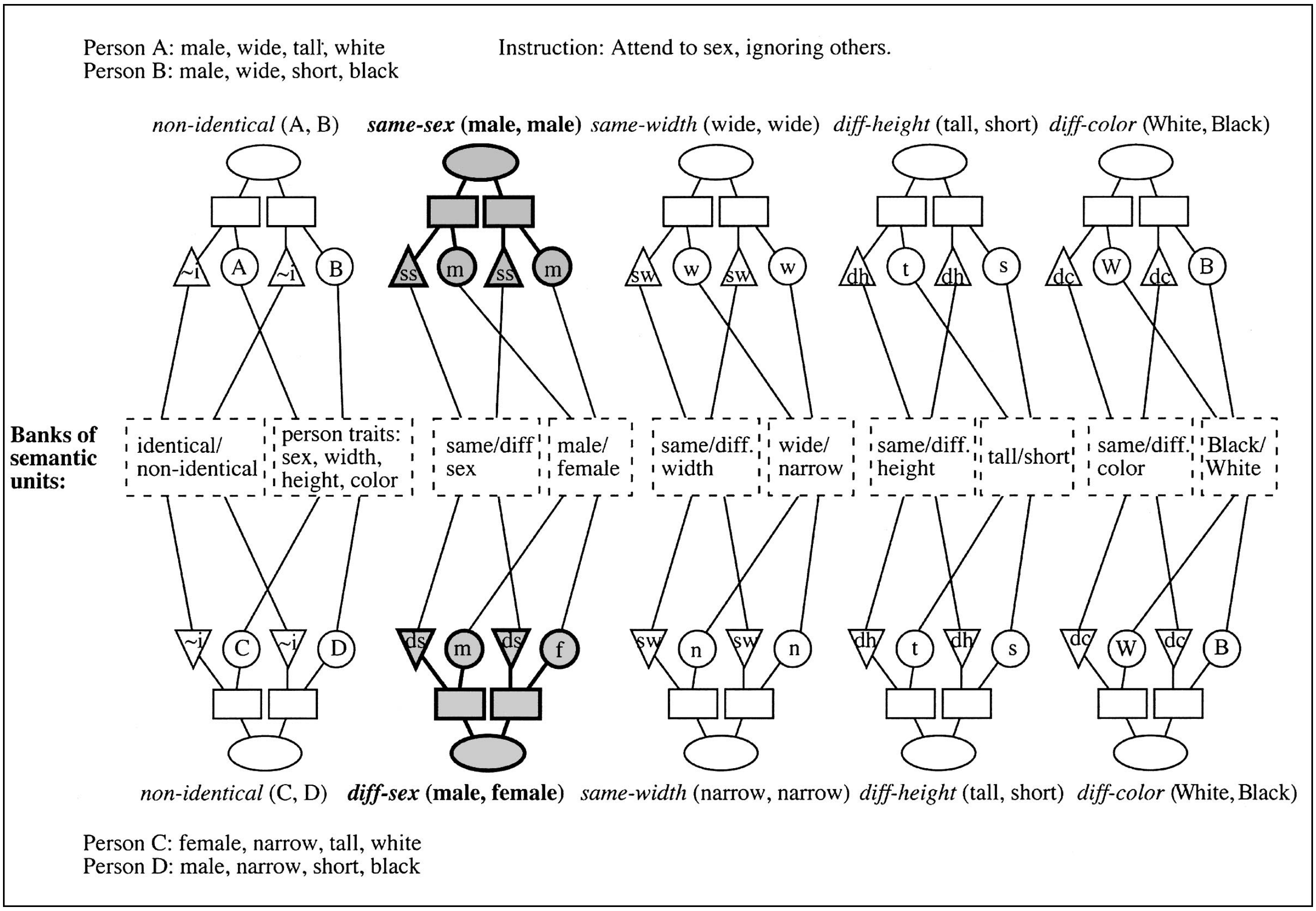

Figure 7. Learning and inference with schemas and analogies representation of a People Pieces Analogy problem in which the participant is to only attend to one attribute (gender). This problem is false because the gender relation for the first pair of characters is same-sex (ss), whereas it is different (diff)-sex (ds) for the second pair of characters. i = identical; ~l = nonidentical; m = male; f = female; sw = same width; w = wide; n = narrow; dh = different height; t = tall; s = short; dc = different color; W = White; B = Black.

performance changes that we have observed on a variety of reasoning tasks requiring relational integration.

Discussion

In the People Pieces Analogy task, all participant groups made more errors at higher levels of complexity; the older group performed much less accurately than either the middle-aged or the younger group at all levels. While performance was near ceiling for young and middle-aged participants at Complexity Levels 1 and 2, differences between these groups emerged for response times. Although middle-aged people performed more like younger people in terms of accuracy, they performed more like older people in terms of response times. All groups showed an increase in response time with increasing levels of complexity, although middle-aged and older groups showed a steeper increase, demonstrating that they find higher levels more taxing than do younger people. These results indicate that while older adults have difficulty even at low levels of relational complexity, middle-aged people can still perform relational integration but require more time to do so.

In addition, the results demonstrate that aging is associated with increased difficulty with problems that require the inhibition of irrelevant but misleading information. The difficulty of solving the analogy problems increased with the number of irrelevant traits favoring the incorrect response. Older participants suffered relatively greater interference as a result of irrelevant traits, especially at higher levels of relational complexity. The fact that relational complexity and the need for inhibition interacted to produce an even greater deficit for older adults is consistent with the view that both abilities depend on shared executive processes that decline with age.

The current results are consistent with a decrease in working memory efficiency, particularly with respect to the selection of information for processing in working memory. The LISA model (Hummel & Holyoak, 1997, 2003) provides a specific computational instantiation of how relational reasoning may be performed. In the context of this model, the impact of aging can be modeled by an integration of loss of selectivity in attention to information in working memory with a general decline in inhibitory control (Hasher & Zacks, 1988).

In the People Pieces Analogy task, each question requires sequential analysis of the relations between the pairs for each attribute and then a further analysis of whether or not that relation holds between the pairs. The necessity of coordinating the step of evaluating the first pair and comparing the result with the second pair may be particularly sensitive to aging. Age-related slowing has been shown to be greater with increases in coordinative complexity (i.e., when participants are required to coordinate the information exchanged between processing steps; Mayr & Kliegl, 1993). Our results are consistent with this view, in that increases in relational complexity increase the amount of information that must be exchanged between steps. Mayr and Kliegl (1993) suggest that this effect is due to decreases in the efficiency of working memory with age.

Central to analogical reasoning is the need to maintain and manipulate relational representations in working memory, a demand that increases with higher levels of complexity (see Halford, 2005; Morrison, 2005). Gilhooly, Phillips, Wynn, Logie, and Della Sala (1999) found that during performance of the Tower of London task, older adults were more prone to errors and incomplete reasoning during the planning stage than during the stage in which the moves are completed. The authors argue that the planning stage relies more heavily on working memory processes than does the move stage. As noted previously, Mayr and Kliegl (1993) interpreted age-related deficits in tasks requiring coordinative processing in terms of working memory inefficiency. Using the LISA model (Hummel & Holyoak, 1997, 2003), we attempted to simulate our results by assuming that aging is accompanied by deficits in inhibitory processes within working memory. According to the model, reasoning makes use of working memory to orchestrate the precise firing of structural representations and to learn new correspondences. 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). The simulations that we reported for the People Pieces Analogy task suggest that decreases in the effectiveness of attention and inhibition in working memory with age may explain the performance changes that we observed on the People Pieces Analogy task.

Overall, the declines in reasoning abilities with age that we observed in the current study are consistent with a large body of evidence suggesting that adult working memory efficiency decreases with age. By applying the LISA model, we were able to show that a decrease in inhibitory functioning simulates the aging data well. This computational result lends support to previous arguments that failing inhibition (Hasher & Zacks, 1988), coupled with a loss of selective attention (Craik & Byrd, 1982), may be critical to the effective decreases in working memory efficiency with age.

It should be noted that, although older people showed impaired performance on the People Pieces Analogy task, this task does not test crystallized intelligence and semantic knowledge, which appear to be relatively preserved with age (Ackerman & Rolfhus, 1999; Lindenberger & Baltes, 1997). Rather, the task used in the current study taps fluid intelligence, which has been shown to decline with age (Isingrini & Vazou, 1997).

Although the mechanisms responsible for cortical degeneration with age remain unknown, some studies have shown that the prefrontal cortex appears to be especially vulnerable to age effects (for a review, see Raz, 2000). This same region has been implicated in working memory (for a review, see Fletcher & Henson, 2001), relational reasoning (Robin & Holyoak, 1995; Morrison et al., 2004; Waltz et al., 1999), and inhibitory control (Morrison et al., 2004; Shimamura, 2000). Accordingly, it is plausible that changes in the prefrontal cortex are responsible for the reasoning deficits observed in older people. In fact, Winocur and Moscovitch (1990) have noted that older people often perform more poorly than younger people on tasks that are sensitive to frontal lobe damage. Our group has shown that patients with frontal lobe degeneration show profound deficits in relational integration (Waltz et al., 1999) and inhibition (Morrison et al., 2004) in reasoning tasks similar to those used here, and we have modeled the data in LISA using a similar computational approach (Morrison et al., 2004).

In a functional imaging study, Rypma, Prabhakaran, Desmond, and Gabrieli (2001) found that older people showed less activation of the dorsolateral prefrontal cortex when performing working memory tasks than did younger people. In addition, several studies have shown that there is a general decline in blood flow and metabolism in frontal cortex with age (Gur, Gur, Obrist, Skolnick, & Reivich, 1987; Mielke, Herholz, Grond, Kessler, & Heiss, 1992). Although the current study does not provide direct evidence for the hypothesis that prefrontal cortical changes are responsible for reasoning deficits in old age, our findings have elucidated more specifically the nature of these reasoning deficits. Future research directions include comparing the deficits observed in the course of normal aging with those found in patients with frontal damage.

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