Aging, Neuropsychology, and Cognition, 2015
Vol. 22, No. 3, 340–356, http://dx.doi.org/10.1080/13825585.2014.947915

Analogical reasoning and aging: the processing speed and inhibition hypothesis

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(*Received 29 January 2014; accepted 17 July 2014*)

This study was designed to investigate the effect of aging on analogical reasoning by manipulating the strength of semantic association (LowAssoc or HighAssoc) and the number of distracters' semantic analogies of the A:B::C:D type and to determine which factors might be responsible for the age-related differences on analogical reasoning by testing two different theoretical frameworks: the inhibition hypothesis and the speed mediation hypothesis. We compared young adults and two groups of aging people (old and old–old) with word analogies of the A:B::C:D format. Results indicate an age-related effect on analogical reasoning, this effect being greatest with LowAssoc analogies. It was not associated with the presence of semantic distractors. Moreover, the results show that the variance part of the analogy task due to age was mainly explained by processing speed (rather than by inhibition) in the case of old participants and by both processing speed and inhibition in the old–old group. These results are discussed in relation to current models of aging and their interaction with the processes involved in analogical reasoning.

Keywords: analogical reasoning; aging; processing speed; inhibition

Introduction

Analogical reasoning is a central component of human cognition. It plays an essential role in learning and reasoning (Gentner, Holyoak, & Kokinov, 2001; Holyoak, 2005). As a core component of intelligence, analogy-making, which involves understanding and/or generating relations between objects or situations, has been studied extensively in both adults and children. In many cases, analogy-making involves comparing items and finding common relations *between* domains. For example, an analogy of the classic A:B::C:D type, such as fish:sea::bird:sky, would be interpreted in terms of the common "moves in" relation.

Solving analogy problems of this type requires several processes: (1) encoding the items that compose the analogy, (2) looking for and retrieving from memory a relation connecting the two items in the first pair (A and B, e.g., "moves in"), and (3) mapping this relation (e.g., "moves in") on C and a potential D item (e.g., bird with sky) (e.g., Holyoak, 2005). When participants are provided with a set of potential solutions, they search for the D item that shares the same relation with C as the one connecting A and B. The mapping process might not always be straightforward. There are often several potential relations for A–B, of which one will make sense when looking for a relation between C and D. In any case, analogy will involve retrieving semantic information from memory and comparing it

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*Corresponding author. Email: aurelia.bugaiska@u-bourgogne.fr in order to find relationships holding between pairs of items in order to achieve a meaningful mapping between two pairs. It has been emphasized that while the mapping process is taking place, participants often have to inhibit strongly associated items that are irrelevant for the analogy at hand, and they must be flexible in order to find new relations and/or items that make sense in the context of the target analogy (see Richland, Morrison, & Holyoak, 2006; Thibaut, French, & Vezneva, 2010a, 2010b).

In the aging literature, analogical reasoning has been studied with several tasks. Research on aging has shown that reasoning abilities decrease with aging (see Salthouse, 2005). More to the point, using Raven's Advanced Progressive Matrices Test, a test that involves analogical reasoning, Salthouse (1993) showed that the mean accuracy of young and older adults decreased when the number of relations to be processed increased. However, there was a significant correlation between age and the number of correctly solved problems. More recently, two studies involving perceptual analogies by Viskontas and colleagues (Viskontas, Holyoak, & Knowlton, 2005; Viskontas, Morrison, Holyoak, Hummel, & Knowlton, 2004) showed that older adults had difficulty when they had to integrate multiple relations during analogical reasoning. Viskontas et al. (2004) used a novel version of the People Pieces Analogy task (Sternberg, 1977) in which they manipulated the number of relations defining the analogy problems that were defined around four critical dimensions (among others, gender, height). Participants had to say whether the relations between one pair of characters (i.e., two line drawings of human figures) were the same or different as the one in the other pair ("same color" and/or "same gender", etc.). The authors also manipulated the presence of distractors. They found interactions between age and complexity level (number of dimensions to attend to) and between age and number of distractors in response times (RT): the difference between younger participants and older and middle-aged participants increased as the level of complexity increased. They interpreted this finding as the result of the age-related decline in executive processes and more particularly in the ability to select information for processing from working memory (see also Krawczyk et al., 2008; Morrison et al., 2004, who studied frontal patients).

Our main purpose is to manipulate the semantic association strength between the stimuli that compose the pairs and to relate participants' performance for different types of analogies to general cognitive factors explaining cognitive decline. Before presenting our study, we summarize the literature that suggests that cognitive decline in older adults is based on a combination of underlying factors (Zacks & Hasher, 2006). A number of studies have sought to identify factors that predict or mediate age-related differences in a range of cognitive functions (Bugaiska et al., 2007; Clarys, Bugaiska, Tapia, & Baudouin, 2009; Luszcz, Bryan, & Kent, 1997; Salthouse, 1996). This approach assumes that if these factors are responsible for age-related differences in analogical reasoning, their inclusion in a hierarchical regression analysis should reduce age-related variance to a nonsignificant level. Several competing candidates may play this role of mediator: executive functioning (West, 1996), especially inhibition (Salthouse & Zacks, 1988), or processing speed (Salthouse, 1996). In the present study, we focused on inhibition and processing speed.

Inhibition could explain the differences in analogical reasoning between younger and older people. It has been widely reported that older adults are more disturbed by distracting stimuli than younger people (Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999). According to this hypothesis, aging is associated with decreased ability to control interference because inhibitory processes become increasingly less efficient (Borella, Carretti, Cornoldi, & De Beni, 2007; De Beni, Borella, & Carretti, 2007; Kok, 1999; Persad, Abeles, Zacks, & Denburg, 2002; Vallesi, Stuss, McIntosh, & Picton, 2009; for a review, see McDowd & Shaw, 2000). This deficit may cause irrelevant, distracting information to interfere with the content of working memory, taking up limited storage capacity, and, thus, deviate cognitive processing away from current goals (Harnishfeger & Bjorklund, 1994; Hasher et al., 1999). As a consequence, older adults are more likely to process and memorize irrelevant information than younger people (Darowski, Helder, Zacks, Hasher, & Hambrick, 2008; Hamm & Hasher, 1992; Hartman & Hasher, 1991). This greater effect of distraction with advancing age has been obtained in various situations, such as visual search tasks (Folk & Lincourt, 1996; Humphrey & Kramer, 1997; Madden, Gottlob, & Allen, 1999; Whiting, Madden, Pierce, & Allen, 2005) and comprehension and reading tasks (Carlson, Hasher, Connelly, & Zacks, 1995; Connelly, Hasher, & Zacks, 1991; Dywan & Murphy, 1996). In this context, Viskontas and colleagues' results (Viskontas et al., 2004, 2005) showing an age-related decline in reasoning performance may be explained by a decline in attention and inhibitory functions (e.g., distractors to inhibit).

Another explanation of differences in analogical reasoning between younger and older people could be processing speed. According to Salthouse (1996), the speed at which the central nervous system processes information could influence not only the quantity but also the quality of processing. Salthouse (1991) argued that general processing speed accounts for much of the age-related variance in cognitive domains. This theory predicts that older adults will take longer time to complete working memory tasks and that tasks requiring a lot of sequential processing will be impaired as participants run out of processing time. According to this view, mental operations slow down with aging and require extra time, leaving less time to perform subsequent operations. In addition, the output of earlier processing required for later stages may have dissipated before those stages are reached, and older adults might thus lose track of the relations that are to be tested or have already been tested. Numerous empirical investigations have supported this view (see Salthouse, 1996). Thus, increasing the relational complexity of the analogies, and hence the amount of processing required, could lead to poorer performance due to an age-related decline in speed of processing.

To study the effect of aging, we included two older adult groups (old and old–old), as several studies on aging have reported deficits in processing speed and executive functions in participants as young as 65 (Daigneault & Braun, 1993; Salthouse, 1996). However, processing speed decreases rapidly in the eighth decade (Albert, Wolfe, & Lafleche, 1990; Daigneault & Braun, 1993; Mittenberg, Seidenberg, O'Leary, & DiGiulio, 1989; West, 1996). These studies reported a linear decline in processing speed and executive functioning with age. It is thus possible that age-related differences in cognitive functions could be more pronounced with advancing age (i.e., above 70 years). If performance in analogical reasoning is related to processing speed or inhibition, both these factors might affect the old–old adult group more than the old adult group One crucial question is whether one of these two cognitive factors explains more variance than the other, especially in the old adult group.

Goal of the present study

This study was designed to investigate the effect of the complexity of the analogies, by manipulating the strength of semantic association and the number of distractors. In contrast to Viskontas et al. (2004, 2005) who used analogies defined around a limited number of perceptual dimensions, we used semantic analogies of the A:B::C:D type (e.g., nest is to bird what doghouse is to dog) and manipulated the strength of semantic association within the pairs.

As in Thibaut et al. (2010b) with children, we contrasted pairs in which items were highly semantically associated (hereafter, "HighAssoc") with pairs in which items had a lower semantic association strength (hereafter, "LowAssoc"). The association strength between items (e.g., Tulving & Madigan, 1970) refers to the fact that one word immediately comes to mind when another word is given (e.g., *cow* and *milk*) because the two words are highly associated (i.e., strongly entrenched), whereas other, less associated terms are such that hearing A does not immediately bring to mind B (e.g., *child* and *bed* or *snail* and *plant*). In the HighAssoc case, both pairs were built around highly associated items, whereas the LowAssoc analogies were built around pairs in which items were less semantically associated. Thibaut et al. (2010b) speculated that in the case of low association strength, the semantic space has to be searched more thoroughly to find a common relation. Moreover, each word in a pair activates strongly associated concepts that need to be inhibited because they are irrelevant to the current analogy problem. In terms of the two aforementioned general explanatory factors, LowAssoc analogies might be more difficult for older participants either because they have to inhibit irrelevant associated words that have been activated (Hasher & Zacks, 1988) or because searching the semantic space takes more time due to the greater number of options to consider (Salthouse, 1996). A general slowing down in processing speed (Salthouse, 1996) might lead older adults to lose track of the relations that are to be tested or have already been tested. In their paper, Morrison et al. (2004) used a related index, the semantic facilitation index (SFI), which is defined as the difference between the z-score of the word association for the correct pair (C-Target) minus the incorrect pair (C-Semantic Distractor). In these terms, our HighAssoc analogies would have been neutral and the LowAssoc analogies would have a negative SFI. However, the SFI is defined around C on the one hand and both the target and the semantic distractor on the other hand, whereas our high and low cases also involve the A–B pairs. One can also manipulate semantic strength of association through semantic distance *between* the pairs (Green, Fugelsang, Kraemer, & Dunbar, 2008; Green, Kraemer, Fugelsang, Gray, & Dunbar, 2012). For example, semantic distance is lower in "tail:cat::leg:dog" than in "tail:cat::chair:leg." Green et al. discussed these two types of analogy in terms of creativity and showed that left frontopolar cortex activity correlated with semantic distance.

In line with several studies showing age-related differences in inhibition (Hasher & Zacks, 1988; Hasher et al., 1999; Vallesi et al., 2009), we compared young adults to two groups of older adults and old and old–old adults (see "Participants" section). We predicted that older adults, especially old–old adults, would be more disturbed by the presence of two distractors than younger adults. Finally, we studied the interaction between association strength and the number of distractors. When there are no semantic distractors, the analogical solution is always the most strongly associated item in the solution set, even with LowAssoc analogies. By contrast, in the condition with two distractors, older adults are likely to find more difficulty with LowAssoc analogies, which require more inhibition processes (Hasher & Zacks, 1988) and/or more steps to solve the analogy (Salthouse, 1996).

The second objective was to determine which factors might be responsible for the age-related differences in analogical reasoning. In contrast to Viskontas and colleagues, we combined two different theoretical frameworks: the inhibition hypothesis (Hasher & Zacks, 1988) and the speed mediation hypothesis (Salthouse, 1996). In order to contrast the two models of cognitive aging described earlier, we recorded independent measures of inhibition and processing speed in order to assess which of these two factors best predicted age-related variance in analogical reasoning performance. More specifically, we assessed which of these two factors (if any) would explain a decrease in analogical performance in the two old groups.

Method

Participants

A total of 67 adults living in a medium-sized city participated in the study. They were divided into three groups: the first consisted of 23 nonstudent young adults (age range 19–34 years), the second consisted of 22 young-old adults (age range 61–71 years), and the third consisted of 22 (old–)old adults (age range 72–96 years). The two groups of older adults came from the general community and lived in their own homes. They scored above the 27-point cut-off on the Mini-Mental State Examination (Folstein, Folstein, & McHugh, 1975). All participants were volunteers and none were taking medication known to affect the central nervous system.

The demographic characteristics of the three age groups are presented in Table 1. The only differences were, first, between young adults and old adults on verbal ability (as assessed with the Mill-Hill test (Deltour, 1993), a multiple-choice synonym vocabulary test), showing that the old group of adults outperformed the young group, $t(43) = 3.27$, $P = .002$. Secondly, the young group had a significantly higher level of education (in school years) than the old–old group, $t(43) = 2.97$, $P = .004$.

Materials

Analogy task

Each participant completed a total of 24 trials (12 LowAssoc analogies and 12 HighAssoc analogies) divided into four conditions: LowAssoc/0-distractor, LowAssoc/2-distractors, HighAssoc/0-distractor, and HighAssoc/2-distractors. Each condition comprised six trials. Each trial was composed of eight words, corresponding to the A, B, and C items plus five words in the solution set. In the 2-distractor condition, the solution set comprised the analogical match, two words that were semantically related to C, and two that were unrelated, whereas in the 0-distractor condition, it comprised the analogical match and four words that were all semantically unrelated to C. To validate the strength of association of the word pairs used in the HighAssoc and LowAssoc association conditions, 20 adults were asked to rate the strength of semantic association between each pair of words on a scale of one to seven. They also rated the strength of association between C and each of the semantically related distractors. For the A–B pairs, the strength of association was

Table 1. Means and standard deviations of participants' characteristics for the three age groups.

	Young (n = 23)		Old (n = 22)		Old–old (n = 22)	
	M	*SD*	*M*	*SD*	*M*	*SD*
Age (in years)	24.35	4.07	63.31	3.51	78.00	4.92
Education (years)	13.22	1.65	12.77	3.31	10.73	3.65
Mill-Hill	21.56	5.04	26.41	4.88	24.77	6.08
Stroop task	7.37	10.30	−3.26	8.08	−7.90	9.97
Letter-comparison	33.52	6.83	26.95	5.44	18.90	6.01

rated between 2.9 and 4.9 (out of 7, mean 4.17, *SD* = 0.77) for the LowAssoc items and between 5.10 and 6.85 (mean 5.85, *SD* = 0.50) for the HighAssoc items. For the C–D pairs, the strength of association was between 1.9 and 5.7 for the LowAssoc items (mean 4, *SD* = 1.18) and between 4.2 and 6.9 for the HighAssoc items (mean 5.68, *SD* = 0.96). Note that in a HighAssoc analogy trial, both the AB and the CD pairs were highly associated, and in a LowAssoc analogy trial, these two pairs were lowly associated. The strength of association between C and the distractors was strong in both the LowAssoc and the HighAssoc conditions (mean 5.4 in the LowAssoc condition and 5.34 in the HighAssoc condition).

Half the participants saw half LowAssoc and HighAssoc analogies in the 2-distractor condition and the remaining LowAssoc and HighAssoc analogies in the 0-distractor condition, and the remaining participants did the reverse. This was done to avoid any systematic association between a distractor condition and a particular analogy. In other words, half the participants saw one set of 12 analogies per strength of association condition, and the other half saw a different set of 12 analogies per condition.

Inhibition task

The *Stroop Color–Word Test* (Stroop, 1935) was used to measure the inhibition executive component. This task involves three subtests each displaying 100 stimuli. In the first subtest (word reading), the participant is required to read words printed in black ink representing the names of some basic colors. In the second subtest (color naming), participants have to name the color of crosses (XXX). In the last subtest (color–word interference), they have to name the color of the color–word printed in incongruously colored ink (e.g., the word "red" is written in green). In each subtest, participants were required to name the colors aloud as quickly as possible for 45 s, and the number of correct responses was recorded. An interference score was computed as follows: color–word interference score − [(word reading score × color naming score)/(word reading score + color naming score)].

Processing speed task

The *letter–comparison* test (Salthouse, 1990) was used to measure processing speed. Participants were presented with a page containing pairs of letters (X–O). They were instructed to decide whether the two members of the pair were identical or not and to tick the "identical" or "different" column accordingly. The dependent measure was the number of items answered correctly within 30 s.

Procedure

The experimenter saw participants individually. For the analogy task, participants were seated in front of the computer with their eyes approximately 50 cm from the screen. Each experiment began when the experimenter pressed the space bar. The seven stimuli for each analogy trial were displayed simultaneously on the screen. The A:B word pair and the C word were shown in an array with the first two items grouped together on the left of the screen. The C item was on the right of the screen with a box containing a question mark next to it. The five solution words were displayed in a separate row, beneath the A B C ? row (see Figure 1). Participants were given a button box and instructed to press the button whose location on the box corresponded to the correct word on the screen.

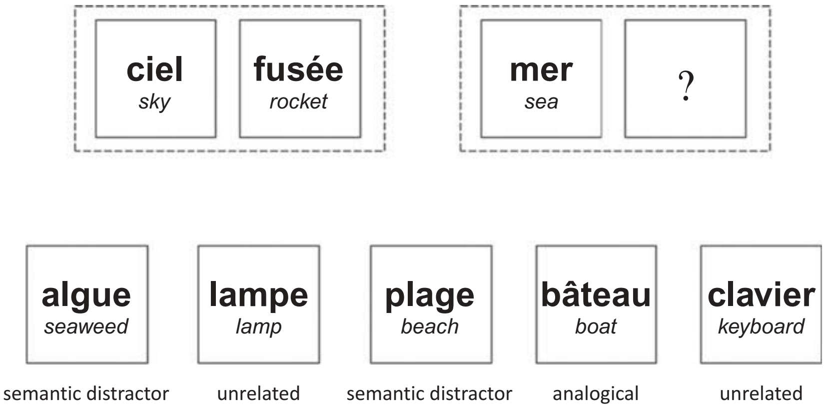

Figure 1. Example of display for weak association/2-distractor condition. The approximate translation of words is written in italics.

In order to avoid any systematic effect of the item's position, the position of each type of word (i.e., analogical match, semantically related distractor, unrelated distractor) was determined randomly from one trial to the next. The first two trials were practice trials. The participants were told that they would have to find analogies, in other words to find a word in the solution set that matched the C item in the same way as A matched B. They were told that there was only one correct answer. RT were recorded for each experimental trial. Participants were instructed to answer as quickly as possible without sacrificing accuracy.

This experiment was a 3 × 2 × 2 mixed design, with age (younger vs. old vs. old–old adults) as between-subjects factor, and strength of association (HighAssoc vs. LowAssoc) and number of semantic distractors (0 or 2) as within-subjects factors. The dependent variables were the number of correct relational matches and the RT computed on correct answers.

Results

We conducted separate analyses on the number of correct responses and RT. For the RT analysis, we considered only the valid relational matches (i.e., the target choices).

Proportions of correct answers

Means and standard errors of the proportion of correct answers are displayed in Figure 2. The analysis of the correct answers revealed a main effect of age, $F(2, 64) = 3.1$, $P < .05$, $\eta_p^2 = .09$, showing that the difference of correct answers was between young and old–old adults, $F(1, 64) = 5.86$, $P = .05$, with less correct answers for the old–old adults. As expected, there were significantly more correct answers with 0 than with 2 distractors, $F(1, 64) = 100.67$, $P < .001$, $\eta_p^2 = .61$. In fact, when there was no distractor, the most obvious item was the relational match. More interestingly, there was a main effect of association, with fewer correct answers with LowAssoc associations than with HighAssoc associations, $F(1, 34) = 28.85$, $P < .001$, $\eta_p^2 = .31$. There was also an interaction between number of distractors and strength of association, showing a difference between

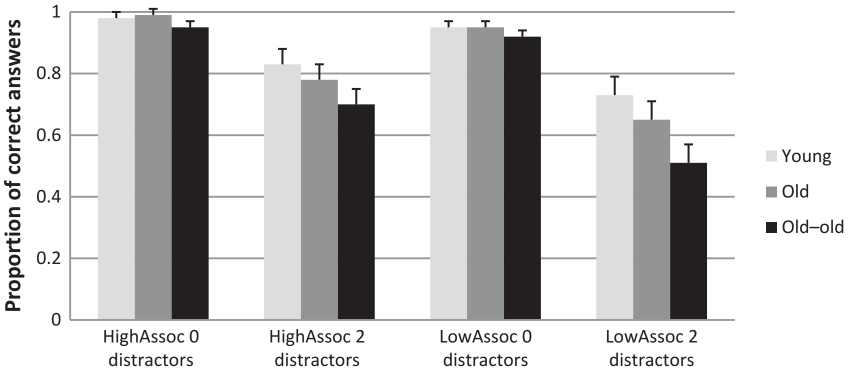

Figure 2. Means and standard errors of the proportion of correct answers as a function of age, number of distractors, and strength of semantic association.

LowAssoc and HighAssoc analogies only in the 2-distractor condition in the LowAssoc and the HighAssoc cases, respectively, whereas performance in the HighAssoc and LowAssoc conditions did not differ significantly in the 0-distractor condition, $F(1, 64) = 11.00$, $P < .01$, $\eta_p^2 = .15$. This result is analogous to the one obtained by Thibaut et al. (2010b) with young children, showing that there was a greater difference between HighAssoc and LowAssoc analogies when there were two distractors than when there was no distractor.

Response times

Means and standard errors of the RT are displayed in Figure 3. We performed the same analysis of variance on the RT for correct answers (in seconds). There was a main effect of age, $F(2, 62) = 12.50$, $P < .001$, $\eta_p^2 = .29$. Fisher's least significant difference (LSD) tests showed that old–old adults took longer than the younger and old adults, but there was no difference between the old and young adults. A significant effect of association strength appeared, $F(1, 62) = 58.74$, $P < .001$, $\eta_p^2 = .49$, and a significant interaction

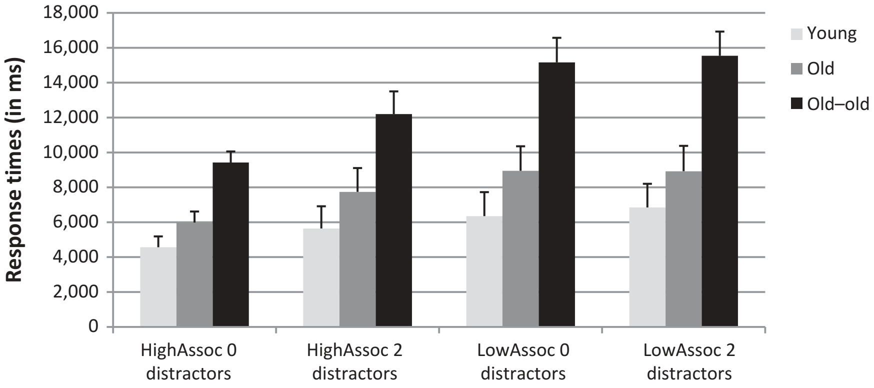

Figure 3. Means and standard errors of the response times as a function of age, number of distractors, and strength of semantic association.

between association strength and age, $F(2, 62) = 6.87$, $P = .002$, $\eta_p^2 = .18$. Fisher LSD tests showed significant differences between HighAssoc and LowAssoc for old and old–old adults, but no difference for younger adults. For HighAssoc, results indicated that the only difference was between old–old adults and younger adults. For LowAssoc, no difference emerged between young and old adults, but differences between old–old adults and young and old adults appeared suggesting that old–old adults are more disturbed by LowAssoc compared to the two other age groups. As shown in Figure 3, this interaction resulted from a greater difference between old–old adults on the one hand and young and old adults on the other hand for LowAssoc analogies than for HighAssoc analogies. This is consistent with our hypothesis that LowAssoc analogies involve a larger semantic space (partly because the analogical relation is less salient), which means that it is necessary to explore more options. No effects related to number of distracters are significant, all Fs < 1.6, ns.

Correlations between group, processing speed, inhibition, vocabulary, education, and strength of association

The first analysis revealed no relation between age and the number of distractors. For this reason, we collapsed the scores for the two distractor conditions into a single score. Thus, the only factor was the strength of association (HighAssoc vs. LowAssoc). We first computed total correlations and correlations for each age group between vocabulary, education, inhibition, and processing speed on the one hand and strength of association on the other (see Table 2). As recommended by Bryan and Luszcz (1996), we used the age group variable rather than individual age in the correlation analyses. As participants were sampled from three age groups, age was not normally distributed in this study, and correlations involving this type of distribution tend to be inflated because of overestimation of the range of scores. Therefore, age was coded as a qualitative variable (young = 1, old = 2, old–old = 3). HighAssoc and LowAssoc analogies correlated with education, inhibition, and processing-speed measures. No significant correlations emerged between vocabulary and HighAssoc and LowAssoc analogies. For young adults, analysis revealed relation between inhibition and HighAssoc and between inhibition, processing, and LowAssoc. For older adults, correlations between processing-speed measures and HighAssoc and LowAssoc emerged. Finally, correlation analyses for old–old group showed relation between inhibition, processing speed, and

Table 2. Pearson correlations between high association, low association, vocabulary, study (in years), inhibition, and processing-speed measures.

	HighAssoc				LowAssoc			
	Young	Old	Old–old	Total	Young	Old	Old–old	Total
Stroop task (inhibition)	−.47*	−.15NS	−.68***	−.56***	−.49*	−.14NS	−.64***	−.56***
Letter-comparison task (processing speed)	−.39NS	−.57**	−.63**	−.65***	−.43*	−.51*	−.62**	−.65***
Mill-Hill (vocabulary ability)	−.27NS	−.26NS	−.13NS	−.22NS	−.39NS	−.33NS	−.29NS	−.13NS
Study (years)	−.09NS	−.28NS	−.58**	−.54***	−.21NS	−.20NS	−.45*	−.48***

Notes: $^*P < .05$; $^{**}P < .01$; $^{***}P < .001$; NS: nonsignificant.

education between HighAssoc and LowAssoc. On the basis of these age group correlations, we conducted regression analyses to assess which of the correlated factors would explain analogy performance differences between young adults and the two old-age groups and between old and old–old adults.

Hierarchical multiple regression analyses

To examine whether age-related differences in education, inhibition, and processing-speed-mediated age-related differences in the two association strength conditions (high vs. low), we used hierarchical regression procedures in order to compare the amount of variance explained by age in the analogy tasks with the amount when controlling for age-related differences in inhibition and processing speed. More specifically, this type of regression involves, first, assessing the effects of age on a criterion variable (here analogical performance) and, second, assessing the effects of age on the criterion variable after partialling out the contribution of another variable (here, either processing speed, inhibition, or education). The difference between the effects of age assessed alone and after statistical control of the predictor variable represents the amount of unique regression, i.e., differences in the criterion variable mediated by the prediction variable (see Salthouse, 1995, for a discussion of this kind of regression analysis). The results of these analyses are shown in Table 3. Only factors correlated with the HighAssoc and LowAssoc for each group were entered in regressions.

First, we assessed which factors would explain the age-related difference between young and old adults (for LowAssoc only, since no age difference emerged in HighAssoc) and between young and old–old adults (for LowAssoc and HighAssoc). Secondly, we assessed which of factors explained the age-related difference between old and old–old adults (for high and low associations).

Comparisons between young versus old adults group and between young versus old–old adults group

First, regarding the LowAssoc condition for old versus young adults, Model 1 shows that age predicted 11% of the variance when entered alone, which is significant. By definition,

Table 3. Hierarchical regression analyses in analogical reasoning: young versus old adults and young versus old–old adults.

	Variable	% of variance	% of reduction	$t(40)$
HighAssoc condition: young versus old–old adults				
	Age group alone	.31	—	4.55***
Model 1	Age group after processing speed	.01	97	.78NS
Model 2	Age group after inhibition	.07	77	1.76NS
Model 3	Age group after education	.19	39	3.17**
LowAssoc condition: young versus old adults				
	Age group alone	.09	—	2.25*
Model 1	Age group after processing speed	.02	79	.97NS
LowAssoc condition: young versus old–old adults				
	Age group alone	.31	—	4.60***
Model 1	Age group after processing speed	.02	93	.87NS
Model 2	Age group after inhibition	.08	74	1.92NS
Model 3	Age group after education	.21	32	3.33**

Notes: ***$P < .001$; **$P < .01$; *$P < .05$; NS: nonsignificant.

this represents 100% of the age-related variance. Partialling out the processing-speed measure reduced the age-related variance to a nonsignificant level and explained 79% of the age-related difference in the low association task.

For the old–old age group (vs. young), regarding the HighAssoc condition, Model 1 shows that age predicted 31% of the variance when entered alone, which is significant. Partialling out the processing-speed measure reduced the age-related variance to a nonsignificant level and explained 97% of the age-related difference. Model 2 shows that inhibition explained 77% of the age-related variance and reduced it to a nonsignificant level. Model 3 indicates that education explained 39% but the age-related variance continued to be significant. Concerning the LowAssoc condition, Model 1 shows that age group predicted 31% of the variance when entered alone, which is significant. Partialling out the processing-speed measure reduced the age-related variance to a nonsignificant level and explained 93% of the age-related difference in the low association task. Model 2 shows that inhibition explained 74% of the age-related variance and reduced it to a nonsignificant level. Model 3 indicates that education explained 32% but the age-related variance still predicted a significant percentage performance once this factor had been controlled for.

Comparisons between old and old–old adults groups

In order to explain which factors would explain the difference between old and old–old groups in HighAssoc and LowAssoc, we conducted two regression analyses. This is interesting because this comparison of two aging subgroups allows us tracking additional aging effects in very old age.

First, in the LowAssoc condition, Model 1 shows that age group predicted 17% of the variance when entered alone, which is significant. Partialling out the processing-speed measure reduced the age-related variance to a nonsignificant level and explained 100% of the age-related difference. Model 2 shows that inhibition explained 41% of the age-related variance. However, the age-related variance continued to predict performance once inhibition had been controlled for. Model 3 indicates that education explained 41% but age-related variance continued to have a significant contribution.

For HighAssoc condition, Model 1 shows that age group predicted 13% of the variance when entered alone, which is significant. Partialling out the processing-speed measure reduced the age-related variance to a nonsignificant level and explained 99% of the age-related difference. Model 2 shows that inhibition explained 38% of the age-related variance reducing the age-related variance to a nonsignificant level. Finally, Model 3 indicates that education explained 46% but the age-related variance continued to be significant (Table 4).

In sum, two important findings emerge from these hierarchical analyses. First, processing speed was the most important factor explaining age-related differences in performance between age groups. Secondly, inhibition only played a role when comparing young and old–old participants, which suggests that inhibition contributes to age-related differences only when age differences increase. We will discuss the significance of these results in the “General discussion” section.

General discussion

In the present experiment, we studied the effect of aging on analogical reasoning. We manipulated the number of semantic distractors and the semantic relatedness within the

Table 4. Hierarchical regression analyses in analogical reasoning: old adults versus old–old adults.

	Variable	% of variance	% of reduction	*t*(39)
HighAssoc condition				
	Age group alone	.13	—	2.53**
Model 1	Age group after processing speed	.001	99	.26NS
Model 2	Age group after inhibition	.08	38	1.86 (*P* = .07)
Model 3	Age group after education	.07	46	1.73 (*P* = .09)
LowAssoc condition				
	Age group alone	.17	—	2.82**
Model 1	Age group after processing speed	.000	100	.01NS
Model 2	Age group after inhibition	.10	41	2.13*
Model 3	Age group after education	.10	41	2.03*

Notes: $^{**}P < .01$; $^{*}P < .05$; NS: nonsignificant.

word pairs. Our second aim was to study whether the effect of ageing on analogy performance can be explained by inhibition (Hasher & Zacks, 1988) or processing speed (Salthouse, 1996). In order to obtain a clearer picture of age-related difficulties in analogical reasoning, we compared old and old–old participants (mean age of 78). This is important and original since most studies compare only two groups, young and old participants. This gives a clearer picture of the dynamics of aging in analogical reasoning.

Our results reveal that participants were influenced by semantic relatedness, and, most interestingly, that this factor interacted with age, and this was our first main goal. Indeed the difference between the three age groups was larger for LowAssoc than for HighAssoc analogies and that the largest difference between the two conditions was in the old–old group. This confirms our hypothesis that the analogical solution does not come to mind immediately in the case of LowAssoc analogies, because the common semantic relation between A and B and between C and D is less salient than with HighAssoc analogies. Indeed, in the LowAssoc analogy condition, highly associated concepts (or words) are activated by each of the four words that compose the analogy (i.e., A, B, C, and D). Since these concepts are irrelevant in the context of the current analogy (e.g., "bone" is associated with "dog", but is irrelevant for the "bird:nest::dog: ??" analogy), they might interfere with the search for the less semantically associated analogical solution. Older participants also had greater difficulty with LowAssoc analogies, which involve a larger semantic search space. As argued earlier (Thibaut et al., 2010a), a larger semantic space leads to more comparisons, more hypotheses to test, and more irrelevant information to discard. This is compatible with studies showing that older adults have difficulty finding a solution when there is interference from other irrelevant information (Carlson et al., 1995; Darowski et al., 2008). This is consistent with Viskontas et al.'s study (2004) with perceptual analogies, in which all groups showed longer RT as the level of complexity increased, but the RT was longest for older adults. In conclusion, our data provide new evidence for the role of the semantic composition of analogies in normal aging. Note that Morrison et al. (2004) found no effect of their semantic facilitation index (see "Introduction" section) in their control group (corresponding to our old group) because it was at ceiling, whereas differences appeared in their frontal patients who were the target of their study.

The second main objective of this article was to determine whether between-group differences in analogical reasoning could be explained by age-related differences in inhibition and processing speed. We focused on RT and the interaction between association strength and age. These results consistently revealed that processing speed was the most important factor explaining age-related differences in performance between age groups. Processing speed was the only significant factor when comparing either young and old participants or old and old–old participants. Inhibition (together with processing speed) only explained a significant amount of age-related variance when young and old–old participants were compared, although processing speed might have played a greater role than inhibition in the HighAssoc situation. In the LowAssoc condition, the two factors seemed to play a similar role.

In sum, when comparing the young and old groups, even though our data show a marked decline in inhibition capacities (see Hasher & Zacks, 1988) and a correlation between inhibition and LowAssoc analogical trials, inhibition was less involved in the age-related variance in analogical reasoning than processing speed. It should be pointed out here, first, that the claim is *not* that inhibition is not involved in analogical reasoning and/or that there is no decline in inhibition capacities with age. Both processing speed and inhibition decline with aging. Secondly, the claim is not that processing speed declines faster than inhibition. Rather, given the set of cognitive processes involved in our analogical task, the point is that one factor, namely speed of processing, explained the age-related decline in analogy performance more than inhibition in most age comparisons.

How can we explain the crucial role of processing speed in aging? One can argue that solving an analogy requires analysis of potential relations not only *within* the pairs, which means testing various attributes, but also *between* the pairs in order to check whether or not each candidate relation holds between the pairs. Coordinating these analyses may be particularly sensitive to aging. Age-related processing-speed decline has been shown to be greater as coordinative complexity increases (i.e., when participants are required to coordinate the information exchanged between steps, Mayr & Kliegl, 1993). Our results are consistent with this view, in that as relational complexity increases, so too does the amount of information that must be exchanged between steps. Moreover, as suggested by Salthouse (1996), older adults take longer time to complete working memory tasks or tasks that require sequential processing, which leads to a drop in performance as participants run out of processing time. Mental operations slow down with aging and require extra time, leaving less time to perform later operations. The output of earlier processing may dissipate before it can be used at a later stage. In this context, because LowAssoc analogies require more sequential comparisons, the results of earlier comparisons may have dissipated before they can be used to solve the problem. Slower processing speed also increases the time needed to test the semantic relations that have been activated, increasing the likelihood of forgetting what has already been done and giving more weight to intrusions.

What is the role of inhibition? As mentioned earlier, our claim is not that inhibition played no role in analogical reasoning in the old group (see Richland et al., 2006 and Thibaut et al., 2010a, 2010b for a discussion of the role of inhibition in analogical development). Rather, our data are consistent with the view that inhibition progressively explains the decline of analogical reasoning when the age groups are very different in terms of inhibition capacities (i.e., young vs. old–old adults). Thus, even though there is a decline in inhibition capacities between young and old participants and between old and old–old participants, this decline is not sufficient to explain age-related differences in analogical reasoning (except in the LowAssoc condition in the comparison between the younger and the old–old groups).

Our results revealed no interaction between age and distractors, which does not rule out the effect of distractors. Indeed, the number of distractors had a main effect on performance. This factor interacted with association strength but not with age. Viskontas et al.'s (2004) results revealed an interaction between number of distractors and age, especially in complex relational conditions, which the authors explained by a decline in attention and inhibitory functions in older adults. One possible explanation for the discrepancy between their findings and ours is that the Viskontas et al. task is more like a relational matching to sample task. Participants have to decide whether the two pairs of cartoon characters are similar or dissimilar in terms of a given target relation (e.g., same gender? Same color?) and this information is inserted in a limited number of other irrelevant dimensions. The task main difficulty is to inhibit these other, irrelevant, dimensions. This would explain why inhibition is important in their case. Indeed, studies on visual search have revealed an age-related deficit in locating a target among heterogeneous distractors (e.g., a red X among red Os and green Xs) (Folk & Lincourt, 1996; Humphrey & Kramer, 1997; Madden et al., 1999; Whiting et al., 2005). It may well be that older people' difficulties in Viskontas et al.'s study increase because the pairs contain dimensions that increase the visual heterogeneity of pairs. Distractors capture the participants' attention and have to be inhibited in order to select the correct answer.

By contrast, as mentioned earlier, our study focused on participants' exploration of an open semantic space in which the relevant semantic relations have first to be identified among many others and, then, tested. A major difference with Viskontas et al. (2004) is that, in our task, the target relation is not given and must be dynamically constructed in the sense that one might first make a guess for the A–B pair, which is then confronted with C and the candidates in the solution set. This first guess might be wrong and another one must be found, especially when relations are not immediately obvious (as in the LowAssoc case). Even though the three groups of participants were influenced by the presence of distractors (main effect of distractors), the specific difficulty in older people, specifically old–old participants, is to build a representation of the relevant relations within a number of potential associations that are activated, keep track of the comparisons already performed, and generate new ones. As mentioned earlier, if mental operations slow down with aging and require extra time, the output of earlier processing may dissipate before it can be used at a later stage. In sum, in our case, the difficulty is to build, compare, and remember a number of relations and hypotheses before each one fade away from short-term memory, whereas in Viskontas et al. (2004), the main issue was to avoid the identification of a target relation being contaminated by irrelevant perceptual information.

Overall, our data show that speed of processing is important in analogical reasoning in the aging context. In the course of aging, inhibition plays an increasing role in analogical reasoning difficulties. The role of executive functions and the prefrontal cortex has been documented. For example, Green et al. (2012), in a sample of young participants, showed that a region in the left frontopolar cortex covaried with increasing semantic distance. According to the authors, this recruitment of the frontopolar cortex would contribute to the integration of semantically distant information when analogies are made between distant domains. Our results showed a larger difference between "distant-LowAssoc" analogies (although the distance index differed from the one used in Green et al., 2012) and HighAssoc analogies in the old–old group. It is well known that the prefrontal cortex is one of the main regions affected by aging (Raz, 2000). Thus, in line with Green et al.'s (2012) data for semantic analogies, we might argue that inhibition difficulties in aging might have contributed to the performance of our old–old group in the LowAssoc condition. This is speculative, because inhibition difficulties in aging have not been precisely associated with the decline of a specific region (see Krawczyk et al., 2008; Morrison et al., 2004, with frontal patients).

To conclude, the results of the present study indicate an age-related effect on analogical reasoning, this effect being greatest with LowAssoc analogies but not in the presence of semantic distractors. We found that when processing speed and inhibition are tested concurrently, processing speed is a better predictor of the age-related differences in analogical reasoning for LowAssoc analogies than inhibition in the old group whereas both inhibition and processing speed were involved in the old–old group. Interestingly, for HighAssoc analogies, both processing speed and inhibition explained the age-related difference in performance.

Acknowledgment

We thank all the participants in the study, Aurélie Breil and Bénédicte Rauly for data gathering, and Laurent Bergerot for his help in programming this study.

Funding

The authors wish to thank the Agence Nationale de la Recherche (ANR) for its financial support (Anafonex project – Blan-2010 – to the first author).

References

Albert, M. S., Wolfe, J., & Lafleche, G. (1990). Differences in abstraction ability with age. *Psychology and Aging*, *5*, 94–100. doi:10.1037/0882-7974.5.1.94

Borella, E., Carretti, B., Cornoldi, C., & De Beni, R. (2007). Working memory, control of interference and everyday experience of thought interference: When age makes the difference. *Aging Clinical and Experimental Research*, *19*, 200–206. doi:10.1007/BF03324690

Bryan, J., & Luszcz, M. A. (1996). Speed of information processing as a mediator between age and free recall performance. *Psychology and Aging*, *11*, 3–9. doi:10.1037/0882-7974.11.1.3

Bugaiska, A., Clarys, D., Jarry, C., Taconnat, L., Tapia, G., Vanneste, S., & Isingrini, M. (2007). The effect of aging in recollective experience: The processing speed and executive functioning hypothesis. *Consciousness & Cognition*, *16*, 797–808. doi:10.1016/j.concog.2006.11.007

Carlson, M. C., Hasher, L., Connelly, S. L., & Zacks, R. T. (1995). Aging, distraction and the benefits of predictable location. *Psychology and Aging*, *10*, 427–436. doi:10.1037/0882-7974.10.3.427

Clarys, D., Bugaiska, A., Tapia, G., & Baudouin, A. (2009). Ageing, remembering and executive function. *Memory*, *17*, 158–168. doi:10.1080/09658210802188301

Connelly, S. L., Hasher, L., & Zacks, R. (1991). Age and reading: The impact of distraction. *Psychology and Aging*, *6*, 533–541. doi:10.1037/0882-7974.6.4.533

Daigneault, S., & Braun, C. M. J. (1993). Working memory and the self-ordered pointing task: Further evidence of early prefrontal decline in normal aging. *Journal of Clinical and Experimental Neuropsychology*, *15*, 881–895. doi:10.1080/01688639308402605

Darowski, E. S., Helder, E., Zacks, R. T., Hasher, L., & Hambrick, D. Z. (2008). Age-related differences in cognition: The role of distraction control. *Neuropsychology*, *22*, 638–644. doi:10.1037/0894-4105.22.5.638

De Beni, R., Borella, E., & Carretti, B. (2007). Reading comprehension in aging: The role of working memory and metacomprehension. *Aging, Neuropsychology, and Cognition: A Journal on Normal and Dysfunctional Development*, *14*, 189–212. doi:10.1080/13825580500229213

Deltour, J. J. (1993). *Echelle de vocabulaire de Mill Hill de J.C. Raven. Adaptation française et normes europeennes du Mill Hill et du Standard Progressive Matrices de Raven (PM38)*. Braine-le-Chateau: Editions l'application des techniques modernes.

Dywan, J., & Murphy, W. E. (1996). Aging and inhibitory control in text comprehension. *Psychology & Aging*, *11*, 199–206. doi:10.1037/0882-7974.11.2.199

Folk, C. L., & Lincourt, A. E. (1996). The effects of age on guided conjunction search. *Experimental Aging Research*, *22*, 99–118. doi:10.1080/03610739608254000

Folstein, M. F., Folstein, S. F., & McHugh, P. R. (1975). Mini-mental state: A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research*, *12*, 189–198. doi:10.1016/0022-3956(75)90026-6

Gentner, D., Holyoak, K. J., & Kokinov, B. (Eds.). (2001). *The analogical mind: Perspectives from cognitive science*. Cambridge, MA: MIT Press.

Green, A., Kraemer, D. J. M., Fugelsang, J., Gray, J. R., & Dunbar, K. (2012). Neural correlates of creativity in analogical reasoning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *38*, 264–272. doi:10.1037/a0025764

Green, A. E., Fugelsang, J. A., Kraemer, D. J., & Dunbar, K. N. (2008). The micro-category account of analogy. *Cognition*, *106*, 1004–1016. doi:10.1016/j.cognition.2007.03.015

Hamm, V. P., & Hasher, L. (1992). Age and the availability of inferences. *Psychology and Aging*, *7*, 56–64. doi:10.1037/0882-7974.7.1.56

Harnishfeger, K. P., & Bjorklund, D. F. (1994). A developmental perspective on individual differences in inhibition. *Learning and Individual Differences*, *6*, 331–355. doi:10.1016/1041-6080(94)90021-3

Hartman, M., & Hasher, L. (1991). Aging and suppression. Memory for previously relevant information. *Psychology and Aging*, *6*, 587–594. doi:10.1037/0882-7974.6.4.587

Hasher, L., & Zacks, R. T. (1988). Working memory, comprehension, and aging: A review and a new view. *The Psychology of Learning and Motivation*, *22*, 193–225. doi:10.1016/S0079-7421(08)60041-9

Hasher, L., Zacks, R. T., & May, C. P. (1999). Inhibitory control, circardian arousal, and age. In D. Gopher & A. Koriat (Eds.), *Attention and performance XVII, cognitive regulation of performance: Interaction of theory and application* (pp. 653–675). Cambridge, MA: MIT Press.

Holyoak, K. J. (2005). Analogy. In K. J. Holyoak & R. G. Morrison (Eds.), *The Cambridge handbook of thinking and reasoning* (pp. 117–142). Cambridge: Cambridge University Press.

Humphrey, D. G., & Kramer, A. F. (1997). Age differences in visual search for feature, conjunction and triple conjunction targets. *Psychology and Aging*, *12*, 704–717. doi:10.1037/0882-7974.12.4.704

Kok, A. (1999). Varieties of inhibition: Manifestations in cognition, event-related potentials and aging. *Acta Psychologica*, *101*, 129–158. doi:10.1016/S0001-6918(99)00003-7

Krawczyk, D. C., Morrison, R. G., Viskontas, I., Holyoak, K. J., Chow, T. W., Mendez, M. F., … Knowlton, B. J. (2008). Distraction during relational reasoning: The role of prefrontal cortex in interference control. *Neuropsychologia*, *46*, 2020–2032. doi:10.1016/j.neuropsychologia.2008.02.001

Luszcz, M. A., Bryan, J., & Kent, P. (1997). Predicting episodic memory performance of very old men and women: Contributions from age, depression, activity, cognitive ability and speed. *Psychology and Aging*, *12*, 340–351. doi:10.1037/0882-7974.12.2.340

Madden, D. J., Gottlob, L. R., & Allen, P. A. (1999). Adult age differences in visual search accuracy: Attentional guidance and target detectability. *Psychology and Aging*, *14*, 683–694. doi:10.1037/0882-7974.14.4.683

Mayr, U., & Kliegl, R. (1993). Sequential and coordinative complexity: Age-based processing limitations in figural transformations. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *19*, 1297–1320. doi:10.1037/0278-7393.19.6.1297

McDowd, J. M., & Shaw, R. J. (2000). Attention and aging: A functional perspective. In F. I. M. Craik & T. A. Salthouse (Eds.), *The handbook of aging and cognition* (2nd ed., pp. 221–292). Mahwah, NJ: Lawrence Erlbaum Associates.

Mittenberg, W., Seidenberg, M., O'Leary, D. S., & DiGiulio, D. V. (1989). Changes in cerebral functioning associated with normal aging. *Journal of Clinical & Experimental Neuropsychology*, *11*, 918–932. doi:10.1080/01688638908400945

Morrison, R. G., Krawczyk, D., Holyoak, K. J., Hummel, J. E., Chow, T., Miller, B., & Knowlton, B. J. (2004). A neurocomputational model of analogical reasoning and its breakdown in frontotemporal lobar degeneration. *Journal of Cognitive Neuroscience*, *16*, 260–271. doi:10.1162/089892904322984553

Persad, C. C., Abeles, N., Zacks, R. T., & Denburg, N. L. (2002). Inhibitory changes after age 60 and their relationship to measures of attention and memory. *The Journals of Gerontology Series B: Psychological Sciences and Social Sciences*, *57*, P223–P232. doi:10.1093/geronb/57.3.P223

Raz, N. (2000). Aging of the brain and its impact on cognitive performance: Integration of structural and functional findings. In F. I. M. Craik & T. A. Salthouse (Eds.), *The handbook of aging and cognition* (2nd ed.). London: Lawrence Erlbaum Associates.

Richland, L. E., Morrison, R. G., & Holyoak, K. J. (2006). Children's development of analogical reasoning: Insights from scene analogy problems. *Journal of Experimental Child Psychology*, *94*, 249–273. doi:10.1016/j.jecp.2006.02.002

Salthouse, T. A. (1990). Working memory as a processing resource in cognitive aging. *Developmental Review*, *10*, 101–124. doi:10.1016/0273-2297(90)90006-P

Salthouse, T. A. (1991). *Theoretical perspectives and cognitive aging*. Hillsdale, NJ: Erlbaum.

Salthouse, T. A. (1993). Influence of working memory on adult age differences in matrix reasoning. *British Journal of Psychology*, *84*, 171–199.

Salthouse, T. A. (1995). Influence of processing speed on adult age differences in learning. *Swiss Journal of Psychology*, *54*, 102–112.

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review*, *3*, 403–428. doi:10.1037/0033-295X.103.3.403

Sathouse, T. A. (2005). Effects of aging on reasoning. In K. J. Holyoak & R. G. Morrison (Eds.), *Cambridge handbook of thinking & reasoning*. New York, NY: Cambridge University Press.

Sternberg, R. J. (1977). *Intelligence, information processing, and analogical reasoning: The componential analysis of human abilities*. Hillsdale, NJ: Erlbaum.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *89*, 669–679.

Thibaut, J.-P., French, R. M., & Vezneva, M. (2010a). Cognitive load and semantic analogies: Searching semantic space. *Psychonomic Bulletin and Review*, *17*, 569–574. doi:10.3758/PBR.17.4.569

Thibaut, J.-P., French, R. M., & Vezneva, M. (2010b). The development of analogy making in children: Cognitive load and executive functions. *Journal of Experimental Child Psychology*, *106*, 1–19. doi:10.1016/j.jecp.2010.01.001

Tulving, E., & Madigan, S. A. (1970). Memory and verbal learning. *Annual Review of Psychology*, *21*, 437–484. doi:10.1146/annurev.ps.21.020170.002253

Vallesi, A., Stuss, D. T., McIntosh, A. R., & Picton, T. W. (2009). Age-related differences in processing irrelevant information: Evidence from event-related potentials. *Neuropsychologia*, *47*, 577–586. doi:10.1016/j.neuropsychologia.2008.10.018

Viskontas, I. V., Holyoak, K. J., & Knowlton, B. J. (2005). Relational integration in older adults. *Thinking & Reasoning*, *11*, 390–410. doi:10.1080/13546780542000014

Viskontas, I. V., Morrison, R. G., Holyoak, K. J., Hummel, J. E., & Knowlton, B. J. (2004). Relational integration, inhibition and reasoning in older adults. *Psychology & Aging*, *19*, 581–591. doi:10.1037/0882-7974.19.4.581

West, R. L. (1996). An application of prefrontal cortex function theory to cognitive aging. *Psychological Bulletin*, *120*, 272–292. doi:10.1037/0033-2909.120.2.272

Whiting, W. L., Madden, D. J., Pierce, T. W., & Allen, P. A. (2005). Searching from the top down: Ageing and attentional guidance during singleton detection. *The Quarterly Journal of Experimental Psychology Section A*, *58*, 72–97. doi:10.1080/02724980443000205

Zacks, R. T., & Hasher, L. (2006). Aging and long term memory: Deficits are not inevitable. In E. Bialystok & F. I. M. Craik (Eds.), *Lifespan cognition: Mechanisms of change* (pp. 162–177). New York, NY: Oxford University Press.