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Working memory and inhibition across the adult life-span

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Abstract

Research has shown that age-related changes in cognitive performance are due mostly to the decline of general factors such as working memory and inhibition. The present study is aimed at investigating age-related changes in these mechanisms across the adult life-span from 20 to 86 years of age. Results indicate a linear relationship between each working memory measure and age, independently of the nature of the task, and a quadratic relationship between the single inhibitory measures and age. Moreover, hierarchical regression analyses show that inhibition accounts for a significant, but modest, part of the age-related variance in working memory. Taken together, these results suggest that inhibition is not as crucial a contributor of age-related changes in the functional capacity of working memory across the adult life-span as previously thought.

PsycINFO classification: 2340; 2343; 2346; 2800; 2860

Keywords: Working memory; Inhibition; Life-span; Aging

1. Introduction

From the processing resources perspective, many age-related differences in cognitive performance can be attributed to age-related differences in a few general constructs (Bjorklund & Harnishfeger, 1995; Hasher & Zacks, 1988; Salthouse, 1991). The decrease in processing resources with aging has been related to the so-called *cognitive primitives*, i.e. working memory, inhibition, and processing speed, which can be considered as variables that influence the cognitive system (e.g., Verhaeghen, Steitz, Sliwinski, & Cerella, 2003). These general constructs have, indeed, become a central feature in explaining age-related differences in older adults in many cognitive domains.

In the case of working memory, intended as the amount of cognitive resources available to store information while at the same time processing incoming or recently accessed information for use in other cognitive tasks (Baddeley, 1986; Baddeley & Hitch, 1974; Shah & Miyake, 1999), a large number of studies have clearly shown a poorer working memory performance in older adults in comparison to younger adults (e.g., De Beni & Palladino, 2004; Li, 1999; McGinnis & Zelinski, 2003; Waters & Caplan, 2001, 2003; Wingfield, Stine, Lahar, & Aberdeen, 1988). Moreover, the correlations between age and working memory tasks are quite consistent, ranging from moderate to large (e.g., DeDe, Caplan, Kemtes, & Waters, 2004; Stine, Wingfield, & Myers, 1990). This pattern of results suggests that aging is associated with a decrease in working memory capacity (for meta-analysis see Bopp & Verhaeghen, 2005; Johnson, 2003). These results, based on extreme group comparisons, are also confirmed by a number of life-span studies in which a decline in working memory was observed with aging (Chiappe, Hasher, & Siegel, 2000; Jenkins, Myerson, Hale, & Fry, 1999; Park et al., 1996, 2002; Siegel, 1994).

With reference to the classical working memory model proposed by Baddeley (Baddeley & Logie, 1999), working memory is considered as a multicomponent system. The specialized components include a central executive that coordinates, controls and regulates information coming

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from domain-specific slave systems that store verbal (phonological loop) and visuo–spatial (visuo–spatial sketchpad) material. Many different working memory measures, with various processing and storage requirements, have been developed for the different domains such as verbal (Reading Span test – Listening Span test; Daneman & Carpenter, 1980; De Beni, Palladino, Pazzaglia, & Cornoldi, 1998) and visuo–spatial (see Vecchi & Cornoldi, 1999). These complex tasks all require the recall of some piece of information after completion of a task that involves some attention-demanding process (reading or listening to a number of sentences; manipulation, transformation and integration of a number of images). Hence, while the individual must maintain a memory representation, a concurrent, distracting, attentional shift takes place (e.g., Engle, Kane, & Tuholski, 1999). The content specialization and organization of working memory is supported by cognitive, neuro-psychological and neuroimaging data. For example, experimental studies have shown selective interference effects within each domain; thus verbal interference tasks selectively interfere with verbal memory, whereas visuo–spatial interference tasks selectively interfere with visuo–spatial memory (e.g., Logie, 1995). Studies with brain damage patients have shown a selective impairment in either verbal or visuo–spatial working memory tasks (Della Sala & Logie, 1993). In addition, brain imaging studies have revealed the activation of different parts of the brain during verbal and visual short-term memory tasks (e.g., Smith & Jonides, 1997).

However, in the context of individual differences due to age, the dissociation between verbal and visuo–spatial working memory appears less clear. In fact, some studies report that older adults compared to younger adults are more impaired in tasks requiring temporary storage and active manipulation of visuo–spatial as opposed to verbal information (Jenkins, Myerson, Joerding, & Hale, 2000; Myerson, Hale, Rhee, & Jenkins, 1999; Tubi & Calev, 1989; Vecchi & Cornoldi, 1999). In contrast, others studies have shown a more important age-related decline for verbal as opposed to visuo–spatial material (Fastenau, Denburg, & Abeles, 1996; Vecchi, Richardson, & Cavallini, 2005). Still further studies employing both verbal and visuo–spatial working memory tasks have shown that older adults have poor working memory performance compared to younger adults in all complex span tasks requiring attentional or controlled processes, independently of type of material presented (de Ribaupierre & Lecerf, 2006; de Ribaupierre & Ludwig, 2003; de Ribaupierre, Lecerf, Leutwyler, & Poget, 1997; Kemps & Newson, 2006; Park et al., 2002; Salthouse, 1995). The generality of the working memory decrease with aging has also been confirmed by a recent adult life-span study by Park et al. (2002), which found a gradual linear age-related decline in working memory processes regardless of task modality (visuo–spatial vs verbal). In addition, Park et al. showed that measures of working memory were so highly correlated that they could not be considered distinct constructs. Contrary to Park et al., however, the meta-analysis by Jenkins et al. (1999) indicated a larger age-related decrease for visuo–spatial than for verbal information processing. Whether there is a more accentuated age-related decline in visuo–spatial than in verbal working memory therefore needs clarification.

One construct often called upon to explain age-related differences in working memory is inhibition (e.g., Bowles & Salthouse, 2003; Hasher & Zacks, 1988; Persad, Abeles, Zacks, & Denburg, 2002). This has led to the hypothesis that inhibition exerts control over the content of working memory by helping prevent irrelevant or no longer relevant stimuli from saturating working memory capacity (e.g., Hasher & Zacks, 1988; Zacks & Hasher, 1994). Indeed, efficient inhibitory mechanisms allow focus on relevant task goals without distraction by non-pertinent information (Hasher & Zacks, 1988). Poor inhibition not only limits but also damages cognitive performance by allowing irrelevant information to intrude and consume limited storage capacity, and by permitting the use of resources for the processing of irrelevant information (Harnishfeger & Bjorklund, 1993). The tendency to keep irrelevant information active has been proposed as one of the sources of age-related decline in working memory. According to Hasher and Zacks (1988), aging coincides with a decrease in the effectiveness and efficiency of an individual ability to control interference. For example, a recent study has shown that with advancing age, inhibitory mechanisms become increasingly less efficient (Persad et al., 2002), with the old-old performing worse on inhibitory measures than the young-old (see also Borella, Carretti, Cornoldi, & De Beni, 2007; De Beni, Borella, & Carretti, 2007). Older adults are less likely to inhibit irrelevant items, and more likely to retrieve them (e.g., Hamm & Hasher, 1992; Hartman & Dusek, 1994; Hartman & Hasher, 1991).

In the context of classical working memory tasks, it has been suggested that poor performance in working memory tasks is associated with an increase in number of intrusion errors (e.g., Carretti, Cornoldi, De Beni, & Palladino, 2004; De Beni et al., 1998; Palladino, Cornoldi, De Beni, & Pazzaglia, 2001), also when older adults are considered (Borella, Carretti, & Mammarella, 2006; De Beni & Palladino, 2004; Palladino & De Beni, 1999). Intrusion errors are a special type of inhibition measure since they are inherent to the working memory task. This measure represents the inability to remove previously activated material no longer relevant (e.g., De Beni et al., 1998; Friedman & Miyake, 2004). Moreover, older adults have been shown to be impaired on more classical inhibitory tests less strictly related to the working memory task – for instance, the Stroop Color test (Schelstraete & Hupet, 2002; Spieler, Balota, & Faust, 1996; West & Alain, 2000) or the Hayling test (e.g., Burgess & Shallice, 1996). In these tasks, a response must be actively suppressed in order for the answer to be given. For the Hayling task, it represents the ability to inhibit predominant and automatic responses yielded by the high-cloze sentences in order to achieve the task goal: produce a word that gives no sense to the sentence. Differences have emerged in this task between young and older adults (e.g., Belleville, Rouleau, & van der Linden, 2006), as well as between control and Alzheimer disease patients (Belleville et al., 2006; Collette, Van der Linden, & Salmon, 1999). Moreover, the ability to complete sentences in the inhibition condition of the Hayling task has been shown to be related to frontal lobe integrity (Burgess & Shallice, 1996). While the above inhibitory measures are objective, there are also more subjective measures of inhibition such as perception of inhibitory failures encountered in everyday life. There are very few studies on the self-perception of inhibitory failure in normal aging (Borella, et al., 2007; Kramer, Humphreys, Larish, Logan, & Strayer, 1994); however, studies with young adults have recently shown that the occurrence of cognitive failures – measured with the Cognitive Failure Questionnaire (Broadbent, Fitzgerald, & Parkers, 1982) – is associated with inefficient inhibitory processes and resistance to distractors (Friedman & Miyake, 2004). Tipper and Baylis (1987) also found that the number of self-reported cognitive failures was inversely related to the magnitude of the negative priming effect.

Nonetheless, more generally the consensus about age-related decline in inhibition is far from universal (see McDowd, Oseas-Kreger, & Filion, 1995), as highlighted, for instance, by a number of meta-analytic studies (e.g., Gamboz, Russo, & Fox, 2002; Verhaeghen & De Meersman, 1998a, 1998b) or studies adopting a life-span perspective (e.g., Borella, 2006; de Ribaupierre et al., 2004). It is also worth noting that the meta-analysis of Verhaeghen and De Meersman (1998a) showed that when processing speed is controlled for, age-related differences in the Stroop effect between young and older adults are not significant, suggesting that a central age-related slowing factor can account for performance.

These results support the recent idea that inhibition is not a general construct, as was initially proposed (see Miyake et al., 2000), and that aging may be associated with selective rather than general decrease in inhibitory function (e.g., Kramer et al., 1994). Another aspect that should be considered when analyzing studies on the role of inhibition in aging is that, apart from a very few studies interested in examining age-related changes in inhibition across the entire life-span (e.g., Bedard et al., 2002; Salthouse & Davis, 2006; Williams, Ponesse, Schachar, Logan, & Tannock, 1999), the literature is dominated by cross-sectional or extreme groups design with different types of populations (e.g., young vs older adults; healthy older adults vs individuals with different cognitive impairments – mild cognitive impairment or Alzheimer's disease).

1.1. Objectives of the study

The aim of the present study was to assess the decline in working memory (considering both verbal and visuo–spatial tasks) and in the efficacy of inhibitory mechanisms from the age of 20 to very old age, thus adopting a life-span perspective. As regards the analysis of life-span changes in different working memory domains, we predict that the rate of decline in working memory is independent of the nature of the task across the adult life-span (Park et al., 2002); this is in line with several individual differences studies (e.g., de Ribaupierre, 2000, 2001; Engle et al., 1999) supporting the notion that working memory serves essentially to hold and process attentional information and is relatively domain free.

In the case of the inhibition account, if inhibition plays a role in explaining age-related differences in cognition (as proposed for example by Hasher and Zacks; see McDowd & Shaw, 2000 for a review), its life-span course should reveal a pronounced decline in coincidence with advancing age, as also shown by Persad et al. (2002). Furthermore, inhibition measures should account for a larger part of variance of working memory performance in comparison to the age factor. To analyze the role of inhibition, we selected a number of inhibitory measures that were either internal (intrusion errors) or external to working memory tasks, and either related to the suppression of dominant responses (Hayling task) or self-reports of "inhibitory" failures (Cognitive Failure Questionnaire).

In selecting the measures tapping into inhibition and working memory, we chose measures that are not based on response times, and thus not related to processing speed. In fact, before interpreting results to support the presence of an inhibitory impairment in older adults, other factors have to be taken into account, such as the speed at which older adults process information (see, Salthouse, 1995; Verhaeghen & De Meersman, 1998a).

2. Method

2.1. Participants

A total of 304 people in the age-range 20–86 participated in the study. Each age decade, from the 20s to the 70s or above, was composed of 49–52 participants (see Table 1). Note that participants aged over 80 were collapsed within the 70s group in order to construct groups of relatively equal sizes.

Participants were all Italian native speakers and volunteered for the study. They were community dwellers and recruited by word of mouth. Older adults were selected on the basis of a physical and health questionnaire. All participants that fitted the "exclusion criteria" proposed

Table 1
Participant characteristics by age group

Age groups			Age (years)		Education (years)	
(years)	*n*	% female	*M*	SD	*M*	SD
20–29	51	65	24.45	2.76	13.96	1.89
30–39	51	53	33.78	2.62	13.11	3.53
40–49	50	68	44.88	3.22	11.14	3.13
50–59	52	63	53.40	2.39	10.73	4.47
60–69	51	67	64.37	3.12	7.59	3.82
>70	49	75	77.29	5.04	5.20	2.77

by Crook et al. (1986) – i.e. history of head trauma; any neurological or psychiatric illness; history of brain fever; dementia or any other state of consciousness alteration; use of benzodiazepines in the previous three months; use of illicit drugs; visual, auditory and/or motor impairment; any symptomatic cardiovascular condition, breathing problems or pathologies causing possible cognitive impairments – were excluded from the study. Older participants were active in the cultural and social activities of the neighborhood. Characteristics of the sample of the six age groups are summarized in Table 1.

The number of females (65%) and males (35%) across the six decades did not differ significantly. However, there was a significant effect of age group on years of education, $F(5, 298) = 50.41$, $p < .001$, $\eta^2 = 0.45$. Post-hoc comparisons indicated that participants aged 60–69 and those aged 70 and above had a lower educational level compared to all other groups, whereas those aged 20–29 and 30–39 had the highest level of education (although they did not differ amongst themselves). Moreover, participants aged 40–49 and 50–59 were not significantly different. Apart from the oldest group considered (aged 70 and above), all had a level of education corresponding at least to completion of compulsory education in Italy.

3. Materials

3.1. Working memory

The Jigsaw Puzzle test – Puzzle – (visuo–spatial task) (Borella, Carretti, & De Beni, 2007 adapted from Vecchi & Richardson, 2000) consists of 27 drawings derived by Snodgrass and Vanderwart (1980). Each drawing is fragmented into 2–10 numbered pieces forming a puzzle. The drawings represent common, inanimate objects with a high value of familiarity and image agreement. Each puzzle is displayed in front of the participant, with the pieces set out in a non-ordered way. These remain available for inspection during the whole period of resolution. Puzzles have to be solved not by moving the pieces but by writing or pointing to the corresponding piece on a response sheet. The level of complexity is given by the number of pieces composing each puzzle (2–10). The final score is computed by summing the score of the three highest levels of complexity correctly solved.

Listening span test – LST – (verbal task) (Borella et al., 2007 adapted from Daneman & Carpenter, 1980). The task consists of an increasing number of 2, 3, 4, 5, 6 sequences of simple sentences. The sequences are grouped into 4 sets composed of four sequences each. For each set, 20 sentences are presented (giving a total of 80 sentences), each separated from the subsequent sentence by an interval of 1.5 s. The sentences vary between 6 and 12 words in length. The last words of the sentences can be composed of 2, 3, 4, or 5 syllables.

Participants are instructed to listen to each sentence, judge its plausibility (state whether it is true or false) and retain the last word. At the end of each set, participants are required to recall all the final words following the correct order of presentation. Two training trials precede the task.

The total number of final words correctly recalled in the correct order during the whole test is considered the measure of the participant's working memory capacity.[1] The number of intrusion errors (words presented in the task that are recalled but not presented in the final position) is also computed. This procedure is intended to measure the ability to exhibit control over the permanence of information in working memory (see for example De Beni et al., 1998).

Categorization working memory span test – CWMS – (verbal task) (Borella et al., 2007 adapted from De Beni et al., 1998). This task is similar to the classical working memory tasks, but requires the processing of lists of words instead of sentences, limiting the role of semantic processing. The material consists of 8 sets of words, each set composed of 18 lists of words, organized into series of word lists of different lengths (from 3 to 6). Each list contains 5 words of high-medium frequency. Lists contain 0, 1, or 2 animal nouns, presented in various locations, including the final position. An example of a list is house, mother, dog, word, night.

Participants listen to the lists of words presented at a rate of 1 s per word, and are required to tap their hand on the table whenever they hear an animal word (processing phase). The interval between the two lists of words is 2 s. At the end of the series, participants must recall the last word of each list in a serial order (maintenance phase). The presentation, therefore, is paced by the experimenter.

The total number of correctly recalled words is considered the measure of the participant's working memory capacity. The number of tapping errors is also measured to take the level of accomplishment of the processing task into consideration. For the LST, the number of intrusion errors (i.e. non-final words incorrectly recalled) is also computed.

3.2. Inhibition

Hayling sentence completion test – Hayling – (Borella et al., 2007 adapted from Burgess & Shallice, 1996, 1997) assesses the efficacy of inhibiting dominant responses. High-cloze sentences in which the last word is missing are presented and must be completed either with an expected word (initiation condition) or by a word providing no meaning to the sentence (inhibition condition). Sentences are selected on the basis of their completion probability (between .98 and .99). Twenty-eight sentences are administered. In each condition, 14 sentences are presented. In the first condition (initiation), 14 high-cloze sentences have to

[1] The use of this score was justified by previous findings demonstrating its reliable psychometric properties (Conway et al., 2005).

Table 2
Correlation matrix

	1	2	3	4	5	6	7
1. Age							
2. Puzzle	−.74***						
3. LST	−.56***	.52***					
4. CWMS	−.68***	.63***	.61***				
5. Hayling (index)	.34***	−.37***	−.15***	−.21***			
6. Intrusions LST	.39***	−.42***	−.61***	−.44***	.14**		
7. Intrusions CWMS	.34***	−.35***	−.37***	−.48***	.14***	.44***	
8. CFQ	−.00	.02	−.03	−.08	−.05	.05	−.06

** $p < .01$.
*** $p < .001$.

be completed with the expected word. In the second condition (inhibition), the other 14 sentences have to be completed with a word unrelated to the sentence content, but fitting it grammatically. Sentences appear in a fixed order for each participant. The presentation order of each condition is fixed: initiation, inhibition. A practice phase (three sentences) is presented before each test condition.

An inhibitory index, based on the differences between the inhibition and initiation phases, is calculated on accuracy responses as follows: correct completions, expected words, for the initiation phase – correct completions, nonsense words, in the inhibition phase. A higher score thus implies a higher difficulty in producing the unexpected word in the inhibition condition.

Cognitive Failure Questionnaire – CFQ – In this questionnaire (Borella et al., 2007 adapted from Broadbent et al., 1982), participants are asked to rate, on a scale from 0 (never) to 5 (very often), the frequencies of 25 everyday cognitive failures. The dependent measure is the sum of the reported frequencies across all the questions.

It is important to note that intrusion errors in both the Listening span test and the Categorization working memory span test, as cited below, are part of the inhibitory measures considered.

3.3. Procedure

The participants were tested in two separate sessions lasting about 90 min each. A delay of one week was set between sessions in order to avoid familiarity effects on tasks presumed to measure the same construct. In the first session, participants completed a health and demographic questionnaire followed by the LST and the Hayling test. In the second session the task order was CWMS, CFQ, and Puzzle. Whilst the LST, Hayling and CWMS were presented in auditory modality, the CFQ and Puzzle were administered as "paper and pencil". To limit the influence of sensory variables (sight and hearing) (see Lindenberger & Baltes, 1997) on test results, the auditory presentation was adjusted to the participants' hearing level. Moreover, for the paper and pencil tasks, all participants were asked whether they found it easy to read the stimuli. All tasks were administrated individually. The order of the tasks within each session was fixed.

4. Results

Correlations between age and test measures of interest were computed (Table 2). Correlations indicated that age was negatively associated with working memory performance and positively correlated with inhibitory performance (intrusion errors in the LST and CWMS, and Hayling index). These results show that performance in working memory tasks declines with age, whereas difficulty in inhibiting no-longer-relevant information, i.e. number of intrusion errors and in suppressing predominant information, as in the Hayling task, increases. Moreover, whereas the correlations within working memory tasks were large, those within inhibitory measures were small.

It should be noted that the CFQ measure does not correlate with age, measures of inhibition, or working memory scores.

Regression analyses were used to evaluate the nature of the decline across the adult life-span in (1) verbal and visuo–spatial working memory and (2) inhibitory measures used. Moreover, the decline across the life-span between working memory and inhibition measures was compared.[2]

Participant performance was first transformed into *z*-scores using the entire sample to facilitate comparisons across variables. As can be seen in Fig. 1, panel a and c, for the working memory measures the decline appeared to be linear, continuous across life-span, older adults having poorer performance than younger adults. In contrast, for inhibitory measures (see Fig. 1, panel b and c), the decline appeared to be steeper in late adulthood. To check these points, regression analyses were carried out with the linear age trend entered as the first predictor, and, in the subsequent step, the quadratic age term (age2) with each of the measures of working memory and inhibition as dependent variables. Results revealed that for the working memory measures the decline emerged as linear, since the age quadratic term was not significant. The percentage of variance

[2] Although the sample was not matched for education, we computed a series of regression analyses entering this variable with age (or age squared) as independent measures on the dependent variables of interest. The outcome indicated that education did not affect results, since the associated beta values were not significant. This variable was therefore excluded from the analyses presented.

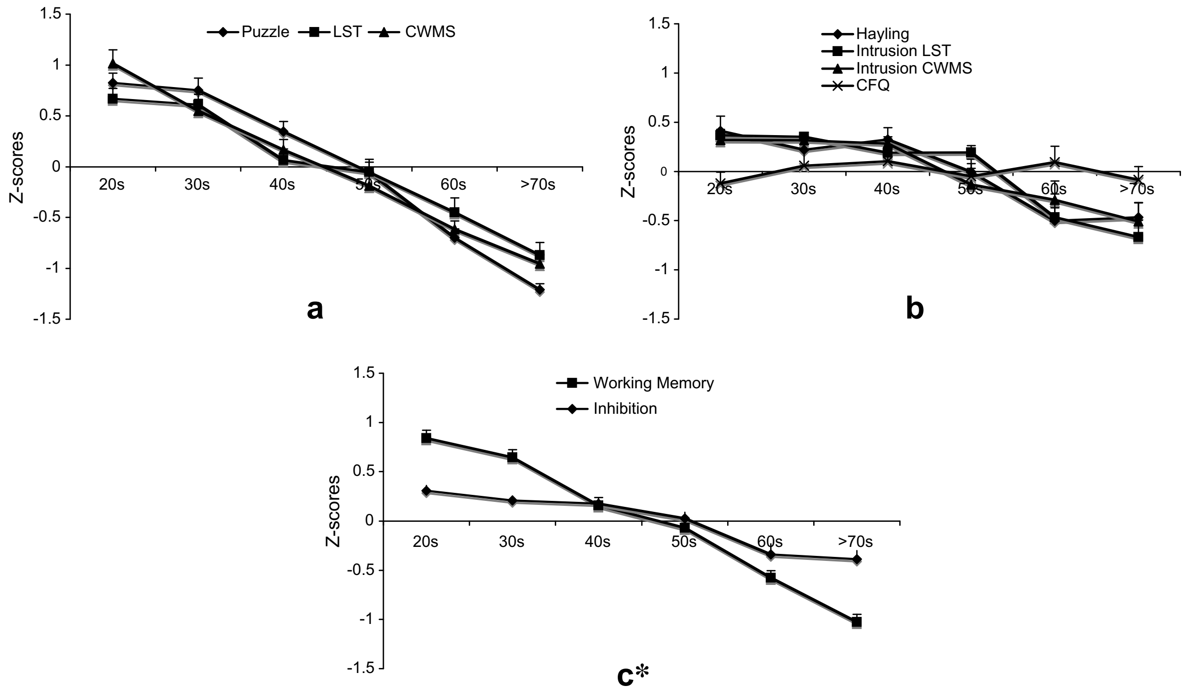

Fig. 1. Life-span measures for working memory (panel a), inhibitory measures (panel b), and a composite view (panel c). Error bars represent standard errors. * Working memory composite score between Puzzle, LST, and CWMS; inhibition, composite score between Hayling, intrusion errors in LST and CWMS, and CFQ.

explained by age for the working memory measures was large (55% in Puzzle, 32% in LST, and 46% in CWMS), with older participants performing more poorly than younger adults. In contrast, for inhibitory measures only, the age quadratic term explained the significant part of the variance, whereas the linear term was never significant. In fact, the quadratic age term explained 16% and 12% of the variance in the intrusion errors in the LST and CWMS, respectively, and 18% in the index on the Hayling test. In contrast, the CFQ, as expected owing to its null correlation with age, did not show any significant change with age.

To further analyze the more crucial role of inhibition in late adulthood, we computed correlation analyses between age and inhibition, dividing the sample into two sub-groups: younger (20–49 years; $N = 152$) and older adults (>49 years; $N = 152$). Standardized scores for the inhibitory measures were computed and an inhibitory factor was created by averaging the *z*-scores (computed within each sub-group) for each sub-group. Results indicated that the correlations between age and inhibitory score factor were marginally significant for the younger sub-group ($r = .15$, $p = .07$), but significant for the older adults ($r = .34$, $p < .001$). In particular, for older adults, age correlated with all the inhibitory measures used (LST intrusion errors: $r = .30$, $p < .05$; CWMS intrusion errors; $r = .19$, $p > .05$; Hayling index: $r = .18$, $p < .05$), apart from the CFQ. Thus, inhibition seemed to have a role – albeit modest – only in the case of late adulthood (see Fig. 1, panel c).

In order to determine whether the rate of decline was more pronounced in visuo–spatial than verbal working memory, confidence intervals of regression analyses were compared for the slopes and intercepts for the three measures of working memory (see Table 3).

This comparison indicated a substantial overlap in the working memory measures. In fact the slopes within the working memory measures did not differ. Hence a single line represents the working memory performance across the adult life-span (see Fig. 1, panel c).

These results can be summarized by stating that the rate of decline in working memory measures is not dependent on the nature of the material (verbal vs visuo–spatial); moreover, the present data provide evidence in favor of a larger age-related decline in working memory than in inhibition. The linear tendency of working memory and the quadratic trend for inhibitory measures (except the CFQ, which did not show any particular change with age) indicate a clear distinctiveness in their ‘‘development’’ across the adult life-span.

Furthermore, hierarchical regression analyses were carried out to assess the extent to which inhibitory efficacy predicts working memory performance, and how age differences on inhibition mediate age differences in working memory. This procedure allows determination of the proportion of variance in working memory that can be attributed to age, inhibition, and the combination of these two variables (e.g., Hertzog, 1996). In fact, age and inhibition were used as predictors as follows: in two distinct steps, age and all inhibitory measures were entered as single predictors in order to assess the amount of age-related variance in working memory that can be accounted for by age and inhibitory measures, respectively. Finally, both age and all

Table 3
Comparing regressions of working memory standardized performance with age

Dependent variables	Slope	Slope SE	Intercept	Bonferroni CIs for slope			
				Intercept SE	R^2	LL	UL
Working memory							
Puzzle	−.041	.002	2.03	.113	.55	−.036	−.046
Listening Span	−.031	.003	1.54	.139	.32	−.024	−.038
Categorization span	−.037	.002	1.86	.123	.46	−.032	−.042

Note: $N = 304$, $p < .001$ for all R^2. Bonferroni confidence intervals (CIs) are based on $\alpha = .05$ for the family of comparisons. LL = lower confidence interval, UL = upper confidence interval.

inhibitory measures were entered together as independent variables. The proportion of variance unique to age and to inhibition, and the variance shared by both predictors, were thus assessed. A *z*-score composite average was created by averaging the *z*-scores of each of the working memory measures, and this composite score was used as the dependent variable. Results indicated that age, ($F(1, 303) = 464.57$, $p < .001$, $R^2 = .61$, $\beta = -.78$), accounted for a large part of the variance in working memory performance, while age and inhibition together explained 71% of the variance. Inhibition, in turn, accounted for a more modest but still significant part of the variance, ($F(4, 303) = 55.88$, $p < .001$, $R^2 = .43$). In particular, all the inhibitory measure, but not the CFQ, contributed to explaining variance in working memory (LST intrusion errors: $\beta = -.44$, $p < .001$; CWMS intrusion errors: $\beta = -.25$, $p < .001$; Hayling index: $\beta = -.19$, $p < .001$). Moreover, the part of the variance unique to age was 28%, ($F(5, 303) = 145.96$, $p < .001$, $\beta = -.62$), and to inhibition 10%. The amount of age-related variance shared with inhibition was 38%. It is worth noting that once age was entered into the regression, only the intrusion errors in the LST ($F(5, 303) = 145.96$, $p < .001$, $\beta = -.27$), and CWMS ($F(5, 303) = 145.96$, $p < .001$, $\beta = -.14$) made a significant contribution to the variance in working memory.

These results support the role of inhibitory processes in working memory performance. Nevertheless, our results also suggest that the association observed between inhibition and working memory is attributable to the variance shared with age by some of the inhibitory measures. Finally, this pattern of results calls into question the generality vs specificity of inhibition in explaining age-related variance in working memory.

5. Discussion

The aim of the present study was to assess changes of both inhibition and working memory across the adult life-span. Whereas "developmental" changes in working memory across adulthood have been well defined, it is unclear whether there is a corresponding age-related decline in inhibition. Many cross-sectional studies have indeed shown that when controlling for speed of processing, age-related changes in the efficacy of inhibitory mechanisms between young and older adults disappear (e.g., Salthouse, 1996; de Ribaupierre et al., 2004; Kramer et al., 1994; Verhaeghen & De Meersman, 1998b). Moreover, though a variety of studies have shown an age-related decline in working memory processes, there are conflicting results when taking into account the verbal or visuo–spatial nature of the tasks presented.

Results of the current study indicate a linear life-long decline in working memory; indeed, the rate of decline appears continuous across the adult life-span, with no acceleration in late adulthood. In addition, the nature of the working memory tasks, verbal or visuo–spatial, has no impact on the rate of decline. It is worth noting that visuo–spatial working memory was measured with only a single task, in which participants were required to both maintain and process an increasing amount of information; therefore active, voluntary controlled operations had to be performed on stored visuo–spatial information. The use of a single measure might raise doubts as to the reliability of our results; however, the high correlations with the other verbal working memory tasks confirm that this visuo–spatial task can indeed be considered a working memory measure.

Although it can be argued that the absence of a differential age effect for verbal and visuo–spatial material can be attributable to the use of non-parallel verbal and visuo–spatial versions, similar results were obtained in studies involving comparable verbal and visuo–spatial tasks. Kemps and Newson (2006), for instance, using verbal and visuo–spatial tasks matched for type of processing (except for modality), showed that memory for verbal and visuo–spatial information declines at comparable rates with aging. Furthermore, the equivalent rate of decline of verbal and visuo–spatial working memory tasks emerging from our data is congruent with previous studies such as those of Park et al. (1996, 2002) and Salthouse (1995), which found no differential rate of decline in the verbal and visuo–spatial domains.

Our data therefore seem to be in line with the view that working memory measures capture a domain general capacity (Engle & Kane, 2004), and suggest that the decline in general resources is more central in explaining age-changes than aspects linked to the modality of the to-be-processed information. The assumption that working memory is a non-specialized single unitary resource emerges from studies in which working memory tasks dealing with different materials-verbal and numerical or visuo–spatial – showed significant and similar correlations with complex abilities (e.g., reading comprehension, intelligence) (de Ribaupierre & Lecerf, 2006; Turner & Engle, 1989, 1986). In the present study, we found no difference between the correlations strength (Morse, 1999) of the two verbal working memory tasks, and between these tasks and the visuo–spatial working memory task.

At the same time, it should be noted that, to date, no cognitive model on aging has raised issues about organization of working memory by content. Nonetheless, some studies suggest that with aging, resources (abilities) become less specialized and less differentiated, and they develop into a more general resource. This de-differentiation hypothesis, initially proposed in 1970 by Reinert, is supported by both behavioral data showing an increase in inter-domain cross correlations only in older adults (see Lindenberger & Baltes, 1997), and by neuro imaging studies which for a given task show lateralized activity in young adults but bilateral prefrontal activity in older adults (e.g., Reuter-Lorenz et al., 2000; Smith & Jonides, 1999). As a consequence, the reduced degree of specialized behavior and resource with aging may explain the existence of an indistinct verbal and visuo–spatial pool of resources in late adulthood, contrary to early adulthood (young adults) where abilities are differentiated. It would be very useful to explore this issue through further studies, to allow definition, for instance, of the adult life-span point at which the hypothesized de-differentiation begins.

In the present study, as stated, we focused on one of the mechanisms proposed to explain age-related differences in cognition and working memory. Inhibition was assessed using intrusion errors, indexing the difficulty to suppress no-longer-relevant information for the current goal in two working memory tasks, the Hayling test, assessing the efficacy in preventing predominant but inappropriate responses, and a questionnaire of self-reported cognitive failures (CFQ). We found that decline in inhibitory measures, except for the CFQ, is shallower in younger adults and more precipitous in older adults, starting in the 50s and with an increasingly negative effect in the 60s and 70s decades. The age-related acceleration in late adulthood is provided by the existence of a quadratic trend of age for inhibitory but not working memory measures. This finding is in line with the study by Persad et al. (2002) which suggests that inhibition becomes less efficient with advancing age – although this study only considered young-old and old-old participants. In agreement with Hasher and Zacks (1988) and as indicated in our study by the occurrence of intrusion errors, we also found an age-related increase in task-irrelevant information in working memory. Inhibitory measures (intrusion errors and Hayling index) positively correlated with age only in the older sub-samples, indicating an increase in inhibitory inefficacy only in older participants. Moreover, in contrast to the younger sub-sample, in the older sample the inhibitory measures, except the CFQ, significantly correlated with one another. This is in line with the frontal aging hypothesis, which states that the frontal lobes and in particular the prefrontal regions are implicated in inhibitory control and most affected by aging (e.g., Rabbitt, Lowe, & Shilling, 2001; West, 1996). The decline of inhibitory mechanisms with advancing age is also supported by a recent study showing that older adults activate not only prefrontal areas, as do young adults, but also additional regions, in an attempt to compensate for the decline in inhibitory processes (Nielson, Langeneker, & Garavan, 2002).

It is worth noting that not all the inhibitory measures were significantly related to age: the CFQ measure did not reveal an age-related decline across the adult life-span, and it did not correlate significantly with any of the other inhibitory or working memory measures. The absence of an age-related decline is, however, in line with the study of Kramer et al. (1994), which failed to find any age-related differences between young and older adults. The CFQ, indeed, evaluates a wide range of failures (self-reported frequency of lapses in cognitive control that include perception, memory and action); the presence of different dimensions may thus explain why this measure is not related to the other inhibitory laboratory measures used.

More generally, correlations within inhibitory measures were small to modest, in contrast with those relating to working memory measures. This result supports the idea of a non-generality of inhibitory mechanisms. The existence of specific inhibitory processes is gaining increasing support in the literature. In studies on aging, for instance, very weak correlations have indeed been found between inhibitory tasks (e.g., Rabbitt et al., 2001; Salthouse & Meinz, 1995; Shilling, Chetwynd, & Rabbitt, 2002). Using structural equation modeling, de Ribaupierre (2001) observed that the latent variable of inhibition accounted for almost no variance in the observed inhibitory variables. Recently, Friedman and Miyake (2004) demonstrated, using structural equation models based on young adults, the specificity of inhibitory functions (see also Salthouse, Atkinson, & Berish, 2003). We also attempted to analyze the extent to which inhibition accounts for age differences in working memory with structural equation modeling (LISREL, Joreskog & Sorbom, 1999). However, as other authors such as Park et al. (1996) also found, we were not able to construct an inhibitory latent variable. This pattern of results may be interpreted by reference to the classification of inhibitory functions proposed by Hasher and Zacks (1988). These authors proposed that inhibitory processes have three main functions: determine which activated representations gain entrance into working memory (access function), suppress representations that are irrelevant or no longer relevant to the current goal (deletion function), and prevent predominant but inappropriate responses (restraint function) (Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999). Although Hasher and Zacks never proposed a classification of inhibitory tests that measures/represents these functions, it is possible that the tasks used represent different functions: the intrusion errors may represent the deletion function (e.g., May, Hasher, & Kane, 1999), and the Hayling test the restraint function. Intrusion errors represent information activated either during the processing phase to judge the sentence, or as the final words of previous sentences; this information was thus once relevant but subsequently became irrelevant for the task goal. Participants – in particular the older adults – have greater difficulty in discarding irrelevant information and suppressing it to recall the target information (De Beni & Palladino, 2004). The ability to exclude activated irrelevant information is indeed crucial to the performance of a working memory task (see De Beni et al., 1998). In contrast, in the Hayling test, it is essential to restrain predominant responses (words that complete high-cloze sentences) not compatible with the correct responses (completing the sentence with a nonsense word) from occurring immediately.

Though age differences in working memory are hypothesized to be due to changes in inhibition, there is very little evidence regarding the influence of inhibition on working memory. In fact, very few studies have directly assessed the relationship between working memory and inhibition. Therefore, to determine the role of inhibition as a mediator of age effects on working memory, hierarchical regression analyses were conducted, which parsed the explained variance in working memory into unique and shared components with respect to age and inhibition. In combination, age and inhibition accounted for a significant proportion of the overall explained variance in working memory. However, age accounted for a larger part of the variance in working memory than did inhibition. This is an intriguing finding because it contrasts with the idea that inhibition is a crucial mediator in the influence of age on working memory changes as proposed by various models (e.g., Hasher, Stoltzfus, Zacks, & Rypma, 1991; Houdé, 1996). More interestingly, once age and all the inhibitory measures were entered together, the index on the Hayling test was no longer a significant predictor of age-related variance in working memory, whereas intrusion errors in the Listening span test and Categorization span tests were still significant predictors.

This latter result could be ascribed to the fact that intrusion errors are an inhibitory measure intrinsic to the working memory task: therefore their prominent role in the regression analyses could be due to the variance shared with the measure of working memory recall. In contrast, the lack of prediction of the Hayling task on working memory, once intrusion errors are entered in the regression model, may suggest that their association is attributable to the variance shared by this measure with age.

Generally, the inhibitory functions studied seem to play a less well-defined role in working memory across the adult life-span with respect to age, and only certain inhibition-related processes explain age-related variance in working memory (Dempster, 1993). As highlighted by Oberauer, Süß, Wilhelm, and Sander (2007), the relationship between working memory and inhibition is generally found on a low level of generality; the ability to inhibit dominant information – as in the Hayling task – may therefore be less important and helpful in the successful performance of the working memory tasks presented. We are certainly aware that our results should be replicated using other types of inhibitory measures.

Another aspect that should be considered in interpreting the current results relates to the fact that some cognitive functions that may explain age-related differences in the working memory capacity were not included. For example, a function usually associated with cognitive aging is the speed at which information is processed and therefore cognitive tasks are carried out. It has been shown through robust findings that processing speed mediates the effect of age in a number of tasks, including working memory tasks (e.g., Salthouse & Meinz, 1995). In fact, once controlled for processing speed, processes that are age-sensitive are spared (see Verhaeghen, Cerella, Bopp, & Basak, 2005). Salthouse and Meinz (1995), for instance, found that processing speed is a more crucial predictor than inhibition in explaining age-related variance in working memory tasks. Furthermore, de Ribaupierre (2001) found that both processing speed and inhibition mediated the effect of age on working memory.

To summarize, the results of the present study suggest that inhibition has a role in explaining cognitive functioning only when older adults are taken into account. Nevertheless, its role in predicting working memory performance is strictly related to age variable; in other words, its unique contribution to working memory variance is modest when compared to age. As for the age-related decline in working memory, our results indicate that this is not dependent on the nature of the material (verbal vs visuo–spatial) involved. Furthermore, our results provide evidence in favor of a greater decline in working memory than in inhibition across the adult life-span.

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