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Working memory and inhibitory control across the life span: Intrusion errors in the Reading Span Test

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The aim of this study was to examine to what extent inhibitory control and working memory capacity are related across the life span. Intrusion errors committed by children and younger and older adults were investigated in two versions of the Reading Span Test. In Experiment 1, a mixed Reading Span Test with items of various list lengths was administered. Older adults and children recalled fewer correct words and produced more intrusions than did young adults. Also, age-related differences were found in the type of intrusions committed. In Experiment 2, an adaptive Reading Span Test was administered, in which the list length of items was adapted to each individual's working memory capacity. Age groups differed neither on correct recall nor on the rate of intrusions, but they differed on the type of intrusions. Altogether, these findings indicate that the availability of attentional resources influences the efficiency of inhibition across the life span.

Working memory (WM) is usually referred to as the ability to store and process information simultaneously, in a controlled manner, for use in a variety of situations (Baddeley, 1986; de Ribaupierre, 2000; Engle, Tuholski, Laughlin, & Conway, 1999). It is assumed to have a limited capacity, which implies that the resources have to be shared between concurrent storage and online processing. A well-known and widely used measure of WM is the Reading Span Test (e.g., Daneman & Carpenter, 1980; Delaloye, Ludwig, Borella, Chicherio, & de Ribaupierre, 2008). In this task, participants have to recall the last word of a series of sentences, after having judged the semantic plausibility of each sentence. The Reading Span Test, as well as other such complex span tasks, has been shown to be a good predictor of a number of complex cognitive abilities (e.g., Baddeley, Logie, Nimmo-Smith, & Brereton, 1985; Borella, 2006; Daneman & Carpenter, 1980; Daneman & Green, 1986; de Ribaupierre & Lecerf, 2006; Kyllonen & Christal, 1990; Masson & Miller, 1983; for a review, see Daneman & Merikle, 1996). However, and despite the large body of research conducted in this area, the factors that underlie WM performance still remain unclear. In particular, a major theoretical issue is to determine how the information in WM is controlled and regulated (see Miyake & Shah, 1999). This issue is particularly important for theorists of development and aging, since children and older adults generally exhibit poorer WM capacity and inhibitory control than do young adults. The relationship between these two constructs still is an object of debate among developmentalists and individual-difference researchers, except for the fact that both relate to attentional resources. As will be developed below, some researchers have posited that individual differences in WM capacity are due to a deficit in inhibitory control (e.g., Hasher & Zacks, 1988), whereas others have argued that differences in WM drive differences in inhibitory control (e.g., Engle et al., 1999). The aim of the present study was to specify to what extent WM capacity (operationally defined as WM span or the quantity of relevant information that is retained in WM tasks) relates to inhibition across the life span.

During the last decades, research has consistently shown age-related changes in WM capacity. Several studies have reported that children (e.g., Chiappe, Hasher, & Siegel, 2000; Dempster, 1981; Jenkins, Myerson, Hale, & Fry, 1999) and older adults (e.g., Bopp & Verhaeghen, 2005; de Ribaupierre, 2001; Jenkins et al., 1999; Waters & Caplan, 2001) demonstrate a lower WM span than do young adults. Accordingly, life span studies have reported evidence that WM capacity increases in children,

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reaches a peak in young adults, and declines with aging (e.g., Borella, Carretti, & De Beni, 2008; Chiappe et al., 2000; de Ribaupierre et al, 2004; de Ribaupierre, Lecerf, Leutwyler, & Poget, 1997; Park & Payer, 2006; Siegel, 1994; for a meta-analysis, see Jenkins et al., 1999). Several explanations have been put forward to account for age-related differences on measures of WM capacity.

Some authors have suggested that age differences in WM capacity result from deficiencies in inhibitory mechanisms (Bjorklund & Harnishfeger, 1995; Dempster, 1992; Harnishfeger, 1995; Hasher & Zacks, 1988; Hasher, Lustig, & Zacks, 2007). Inhibition has been defined as a set of attentional control processes whose aim is to keep WM free of irrelevant information. Inhibitory mechanisms determine which activated, goal-relevant representations gain access to WM (i.e., access function), suppress those representations that become irrelevant for task purpose (i.e., deletion function), and prevent any prepotent responses from gaining control over thoughts and actions (i.e., restraint function). Among the three inhibitory functions, deletion is assumed to play a prominent role in estimates of WM capacity. For instance, in the Reading Span Test, if items from previous trials or nontarget words from the current trial are not deleted, WM will be overloaded by irrelevant information. Thus, the probability of recalling goal-relevant information (i.e., the final word of each sentence) is lowered, and performance is hampered (see May, Hasher, & Kane, 1999). Several studies have provided evidence that age differences in WM capacity are related to age differences in inhibitory efficiency. This conclusion has emerged from, among others, studies that have examined intrusion errors produced in WM tasks. These errors consist in recalling nontarget words and are considered to reflect failures in inhibitory function. Intrusion errors in WM tasks were found to be higher for children (Carretti, Cornoldi, De Beni, & Romanò, 2005; Chiappe et al., 2000) and for older adults than for young adults (Borella, Carretti, Cornoldi, & De Beni, 2007; Borella et al., 2008; Borella, Carretti, & Mammarella, 2006; De Beni & Palladino, 2004; Lustig, May, & Hasher, 2001). Furthermore, Chiappe et al. (2000) have examined the type of intrusions made in the Reading Span Test by a sample of skilled and less skilled readers from 6 to 49 years of age. The findings indicated that the rate of nonfinal intrusions (i.e., the recall of nontarget words from the current trial) increased with age (from 10 to 19 years of age) and declined through adulthood (from 29 to 49 years of age) for skilled readers but not for less skilled ones. To summarize, the inhibitory deficit theory posits that the ability to control for the contents of WM through inhibitory processes is what determines WM capacity. However, as was mentioned above, this hypothesis can be reversed.

Some authors have argued that WM capacity is what drives the efficiency of inhibition because inhibition consumes some resources. In particular, Conway and Engle (e.g., Conway & Engle, 1994; Engle, Conway, Tuholski, & Shisler, 1995) have emphasized the role of WM capacity by introducing a resource account of inhibition. Inhibition is conceived as resource demanding and occurs to the extent that the individual has resources available (see Redick, Heitz, & Engle, 2007). Individual differences in inhibition would therefore result from limitations in WM capacity, not from deficiencies in inhibitory mechanisms per se. By administering a negative-priming task under varying conditions of concurrent memory load, Engle et al. (1995) have provided evidence for the WM resource account of inhibition. In this study, participants performed the letter-naming task (i.e., name the red letter and ignore the green letter) while simultaneously performing a WM-demanding recall task (i.e., from zero to four words to remember for a later recall). Results showed that suppression of the to-be-ignored letter was less likely to occur as the recall task required more WM capacity. That is, as the number of items to memorize increased, more and more WM capacity was necessary to perform the memory task, leaving fewer resources available to suppress the distractor. Similar results were found by Roberts, Hager, and Heron (1994) in the antisaccade task. The authors concluded that inhibitory processes are indeed resource dependent (see also Conway, Tuholski, Shisler, & Engle, 1999).

Although the resource-dependent view of inhibition has been developed to account for interindividual variations among young adults, Conway and Engle (1994) argued that this hypothesis also has strong implications for theories of development and aging. Indeed, the authors mentioned that "it is possible that the reduced ability to inhibit as we get older is a result, in turn, of reduced attentional resources" (p. 369). In fact, several other authors have indicated that there are developmental differences in the availability of WM or attentional resources. In particular, developmental neo-Piagetian theorists (e.g., Case, 1985) have suggested that improvements in cognitive performance throughout childhood are due to increases in the efficiency with which cognitive operations can be executed. This increased processing efficiency releases mental resources to be used for the storage of additional information or for the execution of other cognitive processes. Pascual-Leone has proposed several mechanisms to account for developmental change. Particularly relevant to the definition of WM capacity are the two mechanisms (or *hardware operators*) of *M-power* and *Interrupt*, together with the construct of executive schemes (de Ribaupierre & Bailleux, 1994; Pascual-Leone, 1970, 1987; Pascual-Leone & Baillargeon, 1994). M-power serves to effortfully activate relevant information; it is a limited resource that increases up to adolescence, in a stagewise manner. Inhibition (or *I-operator*) is responsible for actively inhibiting or interrupting less relevant or irrelevant information; it becomes more efficient with age in terms of both its scope and its strength of deactivation. Executive schemes are in charge of selecting the information that is to be activated or suppressed; they also change with age, gaining in complexity and in efficiency. The interest of the latter approach is to clearly distinguish between two independent mechanisms that conjointly drive changes in WM capacity: one mechanism responsible for attentional activation of the relevant information and one for attentional suppression or inhibition.

In the present study, we operationally defined WM capacity as the performance achieved in a WM task (the reading span task) and considered that it indexes attentional or processing resources that subsume both attentional activation (e.g., the words to be retained in the reading span task) and inhibition (e.g., the words that are no longer relevant or other words that are processed but do not need to be memorized). In two experiments, we investigated whether and to what extent WM capacity is related to the efficiency of inhibition, as assessed by errors or intrusions of irrelevant information, and whether age differences are relevant in such intrusions, comparing young adults with children and older adults. In Experiment 1, we used a mixed version of the Reading Span Test in which trials of different complexity were administered in a pseudorandomized manner. The task was identical for all the participants. According to an inhibition-based account of WM capacity, children and older adults were expected to recall fewer correct words and to produce more intrusions than would young adults. Furthermore, highly activated information, such as words previously relevant, should be more difficult to inhibit than less activated information (see De Beni & Palladino, 2004). Thus, intrusion errors should consist of more previous final words than nonfinal words. Experiment 2 was designed to specify whether the age-related differences found in the rate of intrusions could be attributed to limits in overall attentional resources, rather than to an inhibitory deficit. In fact, it might be argued that memory requirements of the mixed Reading Span Test are too demanding of attentional resources for children and older adults, leaving them with too few resources available to efficiently control for the contents of WM. The logic is that if inhibition requires attentional resources, inhibiting irrelevant or no longer relevant information is difficult when the participant is engaged in a more demanding WM span task (see Engle et al., 1995). Following this rationale, age differences in inhibitory efficiency should be less important when WM load is adapted to the WM capacity of the participant in each age group. This hypothesis was tested in Experiment 2 by studying intrusion errors in an adaptive version of the Reading Span Test.

EXPERIMENT 1

Method

Participants. Seventy-four children (age, M = 11.36 years, SD = 0.69, range = 10–12; 32 girls), 74 young adults (age, M = 21.30 years, SD = 1.18, range = 19–24; 64 women), 74 young-old adults (age, M = 64.92 years, SD = 2.39, range = 60–69; 56 women), and 74 old-old adults (M = 75.38 years, SD = 3.96, range = 70–88; 51 women) participated in this experiment. Children were recruited from urban primary schools in Geneva. The young adults were undergraduate students at the University of Geneva, participating for course credit. The older adults were volunteers recruited from the community, either from the University of the Third Age of Geneva or through newspaper and association advertisements for pensioners. All of the young and old adults were also asked to rate their health on a scale of 1 (*poor*) to 5 (*excellent*). The participants were screened for fluency in French, and only the participants who spoke French as their first language or those who had been in a French educational setting for more than 5 years were included. Descriptive statistics for the demographic variables of the participants are provided in Table 1 and show age differences similar to those observed in most studies dealing with cognitive aging.

Concerning educational level, a one-way ANOVA conducted on adults showed a significant age-related difference [$F(2,220) = 3.25$, $p < .05$, $\eta_p^2 = .03$]. Comparisons indicated that educational level was only marginally higher for the young-old than for the young adults [$F(1,218) = 5.39$, $p = .06$]; no other difference was significant ($p > .10$).The French version of the Mill Hill vocabulary scale (Deltour, 1998) was also administered to the young, young-old, and old-old adults. A one-way ANOVA on vocabulary scores indicated a main effect of age [$F(2,219) = 17.82$, $p < .001$, $\eta_p^2 = .14$]. As has often been observed in aging studies, young adults had a lower vocabulary level than did both the young-old and the old-old adults ($p < .01$), which were not different from each other.

Finally, the Raven's standard progressive matrices (Raven, Court, & Raven, 1998) were administered to all the participants. A one-way ANOVA on the total number of correct responses yielded a significant age effect [$F(3,290) = 37.53$, $p < .001$, $\eta_p^2 = .28$]. The young adults had higher performance than the three other groups ($p < .01$), which did not differ from each other.

Materials and Procedure. The French adaptation of the Reading Span Test developed in our lab was administered (Delaloye et al., 2008; de Ribaupierre et al., 1997). Fifty-six syntactically simple and short sentences were used. Half of the sentences were semantically correct (e.g., "Children love chocolate"), and half were not (e.g., "Bananas have pockets"). The number of syllables of the final words to memorize was controlled (i.e., only mono- or trisyllabic words). Half the sentences contained two nouns, as in the examples just provided, and half contained one noun (e.g., "One can buy the moon"). These 56 sentences were then randomly assigned to four series of two, three, four, or five sentences (i.e., four trials for each of the four list lengths). The presentation of each series was pseudorandomized in order to prevent the succession of two items from the same set size. The participants were instructed to read a series of sentences on the screen of a computer and to decide whether each sentence was semantically correct or not. The participants also had to memorize the final word of each sentence. At the end of the series of sentences, the participants had to recall orally all the final words that were presented in the series. Two practice trials (of list length two and three) were given before the experiment started.

Two different scores were computed: (1) The total number of correctly recalled words (out of a maximum number of 56) was considered as an index of WM capacity, and (2) the total num-

Table 1
Experiment 1: Participants' Characteristics by Age Group

	Age Group							
	Children		Young		Young-Old		Old-Old	
Characteristic	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Age	11.36	0.69	21.30	1.18	64.92	2.39	75.38	3.96
Education	5.30	0.72	13.00	0.00	14.14	3.71	14.03	3.67
Vocabulary score	–	–	36.45	2.96	39.18	3.54	39.43	3.59
Raven score	41.32	8.58	52.78	4.40	42.24	9.03	40.23	9.59

ber of intrusion errors (i.e., erroneous recall of nontarget words) was considered as an index of the efficiency of inhibitory control. Intrusions were classified as follows (see Chiappe et al., 2000): (1) Previous-list (PR) intrusions were words from previous series (target or nonfinal words); (2) nonfinal (NF) intrusions were words from the current trial but were not final words; and (3) extraneous (EX) intrusions were words that had not been presented in the task. In order to relate the number of intrusions to individual WM capacity, the percentage of intrusions was computed by dividing the total number of intrusions by the total number of correctly recalled words (see Borella et al., 2006).[1] Moreover, to ensure that the participants were not trading off between processing the sentences and remembering the words, an 85% accuracy criterion on the judgment task was required. In total, 3.07% of the participants were rejected from the experiment, and additional participants were tested to replace them.

Results

The mean percentage of correctly recalled words and the mean percentage of intrusion errors were submitted to ANOVAs. The mean effects of age were examined in terms of linear and quadratic trends across the four age groups. Comparisons were corrected using the Bonferroni procedure.

Correct recall. A one-way ANOVA was conducted on the percentage of correctly recalled words. The main effect of age group was significant [$F(3,292) = 36.64$, $p < .001$, $\eta_p^2 = .27$; linear trend, $F(1,292) = 10.62$, $p < .01$; quadratic trend, $F(1,292) = 59.19$, $p < .001$]. Young adults ($M = 89.94$, $SD = 7.96$) recalled a significantly higher number of correct words than did children ($M = 74.44$, $SD = 9.74$) [$F(1,292) = 70.82$, $p < .001$], young-old adults ($M = 76.98$, $SD = 14.14$) [$F(1,292) = 49.55$, $p < .001$], or old-old adults ($M = 72.44$, $SD = 11.97$) [$F(1,292) = 90.32$, $p < .001$]. The young-old adults did not differ significantly from the old-old adults [$F(1,292) = 6.07$, $p = .09$]. Finally, the children differed neither from the young-old adults [$F(1,292) = 1.89$, $p > .10$] nor from the old-old adults [$F(1,292) = 1.18$, $p > .10$].

An ANCOVA was conducted on the percentage of correctly recalled words in order to check whether the results might be ascribed to educational-level differences across age groups. The effect of age remained significant when controlling for years of education [$F(3,289) = 36.10$, $p < .001$, $\eta_p^2 = .27$], which suggests that the age difference in WM capacity cannot be explained solely by differences in educational level across age groups.

Intrusion errors. A 4 × 3 repeated measures ANOVA with age group (children, young, young-old, or old-old adults) as a between-subjects factor and type of intrusion (NF, PR, or EX) as a within-subjects factor was conducted. These data are presented in Figure 1. The main effect of age group was significant [$F(3,292) = 14.44$, $p < .001$, $\eta_p^2 = .13$; linear trend, $F(1,292) = 15.11$, $p < .001$; quadratic trend, $F(1,292) = 14.20$, $p < .001$]. Also, the effect of type of intrusion was significant [$F(2,584) = 98.41$, $p < .001$, $\eta_p^2 = .25$]. Finally, the age group × type of intrusion interaction was significant [$F(6,584) = 6.70$, $p < .001$, $\eta_p^2 = .06$].

Comparisons were performed to further analyze the age group × type of intrusion interaction. The age effect was significant for both NF intrusions [$F(1,292) = 9.07$, $p < .001$] and PR intrusions [$F(1,292) = 9.94$, $p < .001$] and was marginally significant for EX intrusions [$F(1,292) = 2.47$, $p = .06$]. Further analyses of the age group × type of intrusion interaction revealed that the young adults produced fewer NF intrusions than did the old-old adults [$F(1,292) = 24.50$, $p < .05$]. No other age difference was significant for NF intrusions ($p > .10$). Concerning PR intrusions, young adults produced fewer intrusions than did children [$F(1,292) = 8.31$, $p < .01$], young-old adults [$F(1,292) = 20.83$, $p < .001$], or old-old

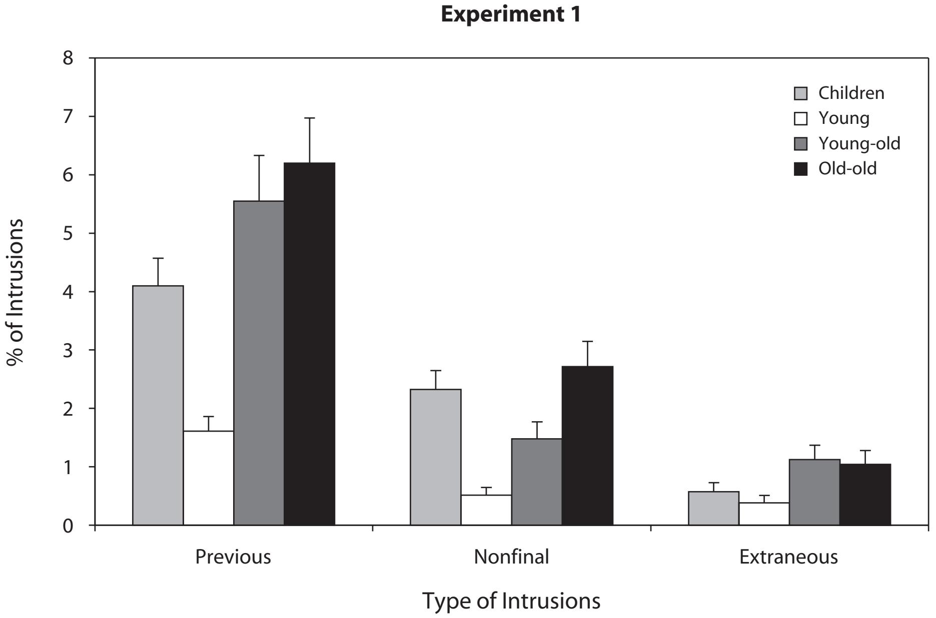

Figure 1. Mean percentages (and standard errors) of previous, nonfinal, and extraneous intrusion errors as a function of age group in Experiment 1.

adults [$F(1,292) = 28.27, p < .05$]. Children made fewer PR intrusions than old-old adults [$F(1,292) = 5.92, p < .05$]. No other difference was significant ($p > .10$).

Comparisons were then conducted within each age group. The children made more PR intrusions than EX intrusions [$F(1,292) = 34.23, p < .001$]. Also, they tended to make more PR intrusions than NF intrusions [$F(1,292) = 8.44, p = .06$] and fewer EX intrusions than NF intrusions [$F(1,292) = 30.19, p = .07$]. No difference in the type of intrusions was significant for the young adults ($p > .10$). The young-old adults made more PR intrusions than both NF intrusions [$F(1,292) = 44.35, p < .001$] and EX intrusions [$F(1,292) = 54.09, p < .001$]. Similarly, the old-old adults made more PR intrusions than both NF intrusions [$F(1,292) = 32.56, p < .001$] and EX intrusions [$F(1,292) = 73.38, p < .001$].

Finally, an ANCOVA was also conducted to check that these effects were not due to age-related differences in educational level. Again, the effect of age and the age group × type of intrusion interaction remained significant when controlling for years of education [$F(3,289) = 15.37, p < .001, \eta_p^2 = .14$, and $F(6,580) = 6.64, p < .001\ \eta_p^2 = .06$, respectively]. Thus, the results cannot be explained by differences in educational level across age groups.

Discussion

First, when the number of correctly recalled words was considered, the results were consistent with previous data showing that WM capacity was higher for young adults than for children and older adults. Second, analyses of intrusion errors were consistent with the hypothesis that the ability to inhibit information is also subject to age-related differences (e.g., Williams, Ponesse, Schachar, Logan, & Tannock, 1999). Altogether, the children and the elderly participants were found to be less able to control for irrelevant information than were the young adults; in particular, they had more difficulty clearing out words that had been previously highly activated (PR intrusions).

To summarize, the present results are clearly consistent with the hypothesis that inhibition is related to WM capacity. However, one can wonder whether age-related differences in intrusion errors are due to deficiencies in inhibitory mechanisms (e.g., Hasher et al., 2007) or to a differential ability to control for attentional resources that would cause differences in inhibitory ability (see Redick et al., 2007). Indeed, when the major part of the attentional resources is consumed by storage, only a small amount of these resources remains available to inhibit irrelevant information. Because the resources available to the system decrease as memory load increases, control for the content of WM becomes more difficult. Accordingly, it can be assumed that the memory requirements of the mixed Reading Span Test are too resource demanding, particularly for children and older adults, so that only a small amount of resources is still available for inhibitory control. Consequently, the apparent age differences could be due to memory load, rather than to inhibitory failures per se. This issue was addressed in Experiment 2 by administering the Reading Span Test with an adaptive procedure instead of a mixed one, as in Experiment 1.

EXPERIMENT 2

The main purpose of Experiment 2 was to examine to what extent inhibitory efficiency across the life span is related to the availability of attentional resources. If the age differences in intrusion errors observed in the mixed Reading Span Test are due to high WM requirements, no age differences should be observed when task level is adjusted to each participant's WM capacity. Furthermore, an increase in list length should generate more intrusion errors and might be more detrimental for children and older adults than for young adults. These predictions were tested by administering a Reading Span Test adapted to each individual's WM span. Note that, in contrast to Experiment 1, it was not possible to distinguish two age groups among the elderly participants (i.e., young-old and old-old), because of a reduced number of participants in this experiment.

Method

Participants. Thirty-four children (age, $M = 11.03$ years, $SD = 0.83$, range = 10–12; 15 girls), 34 young adults (age, $M = 21.12$ years, $SD = 1.63$, range = 19–29; 33 women), and 34 older adults (age, $M = 68.97$ years, $SD = 6.21$, range = 61–85; 24 women) participated in this experiment. None of them had participated in Experiment 1, but selection criteria were identical to those described in Experiment 1. Descriptive statistics for the demographic variables of the participants are provided in Table 2. Educational level was higher for the group of older adults than for the group of young adults [$t(1,65) = 3.14, p < .01$]. As in Experiment 1, older adults' vocabulary scores were higher than those of younger adults [$t(1,65) = 4.81, p < .001$]. Finally, a one-way ANOVA conducted on the total number of correct responses in the Raven task showed a significant main effect of age [$F(2,98) = 49.50, p < .001, \eta_p^2 = .50$], with young adults performing better than the two other groups ($p < .01$).

Materials and Procedure. An adaptive version of the Reading Span Test was administered. The 81 sentences used were similar to those used in Experiment 1 and were randomly assigned to series of 2–7 sentences. The instructions were identical to those described in Experiment 1. However, the adaptive procedure entailed two phases. In the first phase, the WM span level of each participant (level n) was determined. Starting with a span level of two, list length was progressively increased by one. The participants were presented with 3 trials at each list length. Testing was stopped when the participants failed the 3 trials at a given list length. Span was defined by the highest list length at which two out of three words were correctly recalled. In the second phase, 20 trials corresponding to the WM span level of each participant (level n) and 20 trials corresponding to the WM span level plus 1 sentence (level $n+1$) were administered. For example, a participant who had a span level of three (level n) performed 20 trials with 3 sentences (level n) and 20 trials with 4 sentences (level $n+1$). The rest of the procedure and instructions were the same as those used in Experiment 1. The 85% accuracy criterion for the judgment task led to a rejection of 4.44% of the participants and to testing ad-

Table 2
Experiment 2: Participants' Characteristics by Age Group

	Age Group					
	Children		Young		Older	
Characteristic	*M*	*SD*	*M*	*SD*	*M*	*SD*
Age	11.03	0.83	21.12	1.63	68.97	6.21
Education	5.03	0.83	13.00	0.00	14.36	2.53
Vocabulary score	–	–	34.15	3.10	38.56	4.35
Raven score	37.91	6.22	51.59	4.51	38.73	7.90

Table 3
Experiment 2: Percentages of Correctly Recalled Words and Intrusion Errors in the Adaptive Reading Span Test by Age Group

	Age Group					
	Children		Young		Older	
	M	*SD*	*M*	*SD*	*M*	*SD*
List Length *n*						
Correct recall	86.18	7.93	89.00	6.85	87.55	14.71
Nonfinal intrusions	1.93	3.38	1.30	1.94	1.07	2.37
Previous intrusions	1.37	1.84	1.56	1.72	2.01	2.66
Extraneous intrusions	3.26	3.77	2.01	1.78	1.91	2.53
List Length *n*+1						
Correct recall	69.78	11.78	76.72	9.06	71.68	14.43
Nonfinal intrusions	1.84	2.15	1.02	1.80	1.16	1.85
Previous intrusions	1.48	2.18	1.72	1.82	3.84	4.57
Extraneous intrusions	4.72	4.35	1.95	1.84	3.15	6.57

ditional participants to replace them. The measures used to assess performance were identical to those employed in Experiment 1.

Results

The mean span scores (i.e., WM capacity determined in the first phase), the percentage of correctly recalled words, and the percentage of intrusions (collected in the second phase) are presented in Table 3. The data were submitted to ANOVAs. As in Experiment 1, the mean effects of age were examined in terms of linear and quadratic trends across the three age groups. Analyses were corrected using the Bonferroni procedure.

Span scores. A one-way ANOVA conducted on span scores assessed in the first phase indicated a significant age effect [$F(2,99) = 18.91$, $p < .001$, $\eta_p^2 = .28$; linear trend, $F(1,99) = 5.81$, $p < .05$; quadratic trend, $F(1,99) = 32.01$, $p < .001$]. Young adults ($M = 3.62$, $SD = 0.65$) showed higher span scores than did children ($M = 2.50$, $SD = 0.75$) [$F(1,99) = 37.27$, $p < .001$] and older adults ($M = 2.94$, $SD = 0.85$) [$F(1,99) = 13.65$, $p < .01$]. Older adults tended to have higher span scores than did children [$F(1,99) = 5.81$, $p = .05$]. As in Experiment 1, an ANCOVA was run on span scores in order to check that the age effect was not due to differences in educational level. The age effect remained significant when the number of years of education was controlled for [$F(2,97) = 10.22$, $p < .001$ $\eta_p^2 = .17$].

Correct recall. A 3 × 2 repeated measures ANOVA with age group (children, young adults, or older adults) as a between-subjects factor and list length (*n* or *n*+1) as a within-subjects factor was conducted on the percentage of correctly recalled words in the adapted reading span task (measured in the second phase). The results indicated only a main effect of list length [$F(1,99) = 245.04$, $p < .001$, $\eta_p^2 = .71$]. The proportion of correctly recalled words was higher for the *n* list than for the *n*+1 list. Neither the main effect of age group [$F(1,99) = 2.99$, $p = .14$, $\eta_p^2 = .04$; linear trend, $F < 1$; quadratic trend, $F(1,99) = 3.64$, $p = .06$] nor the age group × list length interaction [$F(2,99) = 1.86$, $p = .16$, $\eta_p^2 = .04$] was significant. An ANCOVA indicated that both the age effect and the age group × list length interaction remained nonsignificant when years of education were controlled for [$F < 1$, and $F(2,98) = 1.65$, $p = .20$, $\eta_p^2 = .03$, respectively].

Intrusion errors. A 3 × 3 × 2 repeated measures ANOVA with age group (children, young adults, or older adults) as a between-subjects factor and type of intrusion (NF, PR, or EX) and list length (*n* or *n*+1) as within-subjects factors was conducted. The main effects of list length and type of intrusions were significant [$F(1,99) = 6.18$, $p < .01$, $\eta_p^2 = .06$, and $F(2,198) = 11.06$, $p < .001$, $\eta_p^2 = .15$, respectively]. The main effect of age group was marginally significant [$F(2,99) = 2.80$, $p = .07$]; the quadratic trend of age was significant [$F(1,99) = 5.23$, $p < .05$], contrary to the linear trend ($F < 1$). Finally, the age group × type of intrusion interaction was significant [$F(4,198) = 5.68$, $p < .001$, $\eta_p^2 = .11$]. No other interaction was significant. An ANCOVA indicated that the interaction between age group and type of intrusion remained significant when years of education were controlled for [$F(4,196) = 5.51$, $p < .001$].

The age group × type of intrusion interaction was further analyzed by conducting comparisons (see Figure 2). The three groups of participants differed neither for NF intrusions nor for PR intrusions ($p > .05$). Concerning EX intrusions, the children produced a higher number of intrusions than did the young adults [$F(1,99) = 9.88$, $p < .01$], but they did not differ from the older adults [$F(1,99) = 4.23$, $p > .10$]. The older adults did not differ from the young adults [$F(1,99) = 1.18$, $p > .10$].

Further comparisons conducted within each age group indicated that the children made more EX intrusions than either NF intrusions [$F(1,99) = 14.06$, $p < .01$] or PR intrusions [$F(1,99) = 27.52$, $p < .001$]. No difference in the type of intrusion was significant for the young adults ($p > .10$). The older adults made more PR intrusions than NF intrusions [$F(1,99) = 15.19$, $p < .001$]. No other difference was significant.

Discussion

The results found in the first phase of this experiment (i.e., determination of the individual WM span level) confirmed that children and older adults had smaller WM capacity than did younger adults. In the second phase of the task, the administration of the adaptive Reading Span Test (i.e., adapted to each individual's WM capacity) yielded no significant age effect on the correct recall. Thus, it can

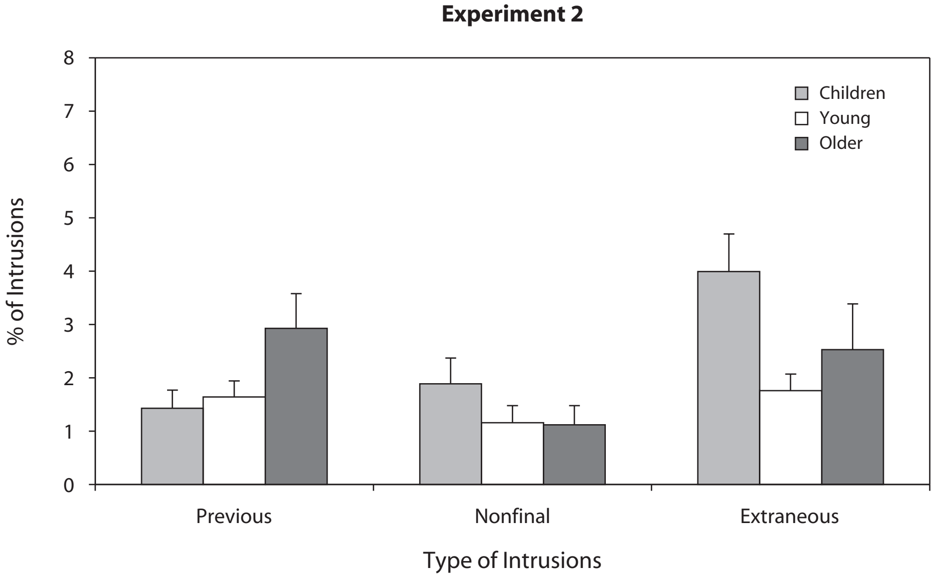

Figure 2. Mean percentages (and standard errors) of previous, nonfinal, and extraneous intrusion errors as a function of age group in Experiment 2.

be assumed that the adaptive procedure we used was really adapted to each participant's WM capacity.

Concerning the indexes of inhibition, it should first be noted that the rate of intrusions increased as list length increased. This is consistent with the idea that the efficiency of inhibitory mechanisms depends on the quantity of available attentional resources (e.g., Redick et al., 2007; Rosen & Engle, 1998). As the number of items held in memory increases, there are fewer resources available to devote to the control of irrelevant information, so the rate of intrusions increases. However, and unexpectedly, the three age groups were equally impaired by an increase in memory requirements, as indicated by the nonsignificant age group × list length interaction on the rate of intrusions. One can argue that level $n+1$ was not really more resource demanding than level n because the increase in memory load represented only one more item to memorize. Note, however, that a reliable main effect of list length was observed on both the correct recall and the rate of intrusions, suggesting that level $n+1$ gave rise to poorer WM performance than did level n. Nevertheless, the increase in memory load might be too small to generate age differences. Another explanation relies on the fact that the increase in WM load was not proportional for all the participants. That is, for individuals with a WM span of two, the increase in memory load from n to $n+1$ corresponded to a 50% greater load (from two to three items to recall), whereas for individuals with a WM span of four, the increase represented a 25% greater load (from four to five words to recall). Further studies that introduce more variations in the size of memory load should be designed to address this issue.

Finally, no age difference was observed for either PR or NF intrusions, although the proportion of PR intrusions was slightly higher in older adults. This suggests that adapting the list length to each individual's WM capacity reduces the age-related difficulty in inhibiting previous- and intralist items. Only extraneous intrusions were found to be age sensitive. In particular, the children made more EX intrusions than did the young adults, which could be interpreted either as a failure to stay task focused or as a strategy of filling the lack of memory with the first item that comes to mind.

COMBINED ANALYSES OF EXPERIMENTS 1 AND 2

Combined analyses of Experiments 1 and 2 were performed to examine whether and to what extent inhibitory efficiency across the life span is affected by the version of the Reading Span Test. A subsample of 34 participants per age group was selected from Experiment 1.[2] A 3 × 2 × 3 repeated measures ANOVA with age group (children, young adults, or older adults) and version of the Reading Span Test (mixed version, adaptive version) as between-subjects factors and type of intrusion (NF, PR, or EX) as a within-subjects factor was conducted on the mean percentage of intrusions. Comparisons were corrected using the Bonferroni procedure.

The main effects of age group and type of intrusion were significant [$F(2,198) = 18.14$, $p < .001$, $\eta_p^2 = .16$, and $F(2,396) = 22.74$, $p < .001$, $\eta_p^2 = .10$, respectively]. However, the main effect of version of the Reading Span Test was not significant [$F(1,198) = 1.92$, $p = .17$, $\eta_p^2 = .01$]. The age group × type of intrusion interaction was significant [$F(4,396) = 7.36$, $p < .001$, $\eta_p^2 = .07$]. Also, the Reading Span Test version × type of intrusion interaction was significant [$F(2,396) = 36.11$, $p < .001$, $\eta_p^2 = .15$]. Comparisons indicated that more PR intrusions were produced in Experiment 1 than in Experiment 2 [$F(1,198) = 23.33$, $p < .001$]; fewer EX intrusions were made in Experiment 1 than in Experiment 2 [$F(1,198) =$

32.19, $p < .001$]; and the same proportion of NF intrusions was made in both experiments [$F(1,198) = 2.77$, $p > .10$]. Finally, the three-way interaction was significant [$F(4,396) = 3.14$, $p < .05$, $\eta_p^2 = .03$], indicating that the pattern of intrusion errors exhibited by the three age groups differed as a function of the version of the Reading Span Test. Comparisons conducted within each age group indicated that the children produced fewer EX intrusions in Experiment 1 than in Experiment 2 [$F(1,198) = 32.88$, $p < .001$] but a similar proportion of PR and NF intrusions in both experiments [$F(1,198) = 7.08$, $p = .11$, and $F < 1$, respectively]. No difference was significant for the young adults ($p > .10$). Finally, the older adults produced more PR intrusions in Experiment 1 than in Experiment 2 [$F(1,198) = 28.13$, $p < .001$]; but the proportion of NF and EX intrusions was similar in both experiments [$F(1,198) = 10.91$, $p > .10$, and $F(1,198) = 1.91$, $p > .10$, respectively].

GENERAL DISCUSSION

The main objective of the present study was to specify to what extent inhibitory control and WM capacity are related across the life span. To do so, the performance of children, young adults, and older adults was compared for the Reading Span Test, which was administered using a mixed procedure (Experiment 1) and an adaptive procedure (Experiment 2). Inhibitory efficiency was assessed through the analysis of intrusion errors. Let us now turn to the relationship between the present findings and those in previous studies and to their theoretical implications.

As concerns WM capacity, age-related differences found between children, young adults, and older adults in both experiments replicated well-known findings found in developmental (e.g., Dempster, 1981), aging (e.g., Bopp & Verhaeghen, 2005), and life span (Jenkins et al., 1999) studies. In the mixed Reading Span Test (Experiment 1), WM capacity was lower in children and older adults than in young adults. This is consistent with the hypothesis that the attentional resources available for storage and processing of information grow from childhood to adulthood and then decline in old age (e.g., de Ribaupierre, 2001). Another explanation that was proposed to explain the development of WM capacity is that the ability to inhibit irrelevant information changes with age (Chiappe et al., 2000; Dempster, 1981; Hasher et al., 2007; Hasher, Zacks, & May, 1999). The results of Experiment 1 were consistent with this hypothesis, because children and elderly people made more intrusions, and particularly previous-list intrusions, than did young adults. Consistent with May et al.'s (1999) view, these data suggest that WM span scores might reflect the ability to inhibit irrelevant information from WM. Nevertheless, these age-related differences could be due to a failure in inhibitory mechanisms and/or to the fact that not enough attentional resources can be devoted to suppression of irrelevant information. Experiment 1 did not make it possible to disentangle these two explanations, because memory requirements of the task were variable depending on the list length of each trial. It is possible that the memory component of the mixed Reading Span Test requires more attentional resources for children and older adults than for young adults, so that the remaining attentional resources necessary for controlling irrelevant information are no longer sufficient. Experiment 2 addressed this issue. By using an adaptative version of the Reading Span Test, proactive interference was found to decrease, and this was particularly true for older adults, who produced fewer PR intrusions.[3] Thus, children and older adults were found to be as efficient as young adults in suppressing highly activated items from previous lists. The high number of extraneous intrusions produced by children can be ascribed to a failure to stay task focused and, in particular, to a difficulty in controlling for extraneous information that has been activated during the task. It can also be suggested that the increase in EX intrusions in Experiment 2 was due to a strategy consisting of filling the lack of memory with the first item that comes to mind. This strategy was more probable in Experiment 2 because the blocked presentation (10 trials at level n and 10 trials at level $n+1$) made it possible to know the number of expected words; in Experiment 1, due to the randomized distribution, the number of words to recall varied from trial to trial.

In summary, the findings from the two experiments support the hypothesis that age differences in WM capacity are due to age differences in attentional resources, necessary to both activate the relevant and suppress the irrelevant information. When the task demand is too high, as seems to have been the case in Experiment 1 for children and older adults, inhibition becomes less efficient. An interpretation of age differences in WM capacity in terms of a deficit in inhibition only is not sufficient. First, controlling for the rate of intrusion errors did not suppress age differences in Experiment 1. Second, there were no longer age differences in intrusions in Experiment 2, once the demand of the task was adapted to the participants. This interpretation should now be further tested by increasing the task demand for young adults too; if an inhibition deficit is not specific to children and older adults but reflects limits in attentional resources, the number of intrusion errors should increase.

An alternative account of the present findings involves age-related changes in source monitoring.[4] Source monitoring "refers to the set of processes involved in making attributions about the origins of memories, knowledge, and beliefs" (Johnson, Hashtroudi, & Lindsay, 1993, p. 3). Most evidence for age-related changes in source monitoring can be found in the aging literature (e.g., Dywan & Murphy, 1996; Hedden & Park, 2003). In text comprehension, Dywan and Murphy found that, contrary to young adults, older adults were less able to inhibit information that had to be ignored. However, younger adults were subsequently more able to recognize this distractive information when it was required by the task. The authors interpreted these findings by arguing that older adults had greater difficulty in distinguishing the source of item familiarity related to both relevant and irrelevant information. Similarly, developmental studies of source monitoring reported that children were more likely than young adults to confuse memories from different sources whenever the sources are highly similar to one another (e.g., Lindsay, Johnson, & Kwon, 1991). In the Reading Span Test, a failure to accurately monitor the source in which each item was initially presented could cause individuals to be unable to discriminate items presented in multiple contexts. That is, if words are presented in multiple contexts (such as in the final vs. the nonfinal position in the sentence), an age-related difficulty in source monitoring would lead to an inability to bind and later recognize the source in which each word was originally presented, while remembering all the words previously processed. Consequently, the probability of making an intrusion error would be increased for children and older adults, which is consistent with the present findings. Furthermore, and assuming that the three types of intrusions reflect different levels of activation, the data found in Experiment 1 suggest that the age-related failures in source monitoring are more salient for highly activated words (i.e., PR intrusions) than for less activated words (i.e., NF and EX intrusions). However, this rationale is not compatible with the findings of Experiment 2, because the pattern of intrusions was clearly different. Thus, even though the source-monitoring explanation can account for some of the age-related changes in the rate of intrusions, the present data cannot provide compelling evidence toward one or the other of these different theoretical accounts. Also, the source and the inhibition explanations are not mutually exclusive. Poorer performance by children and older people could result simultaneously from inhibitory deficiencies and source deficits. Further studies should therefore be designed to disentangle these two accounts.

To conclude, the most important finding was that the difficulty to inhibit irrelevant information in the Reading Span Test was reduced when the task was adapted to each individual's WM capacity (or WM span). This phenomenon was particularly true for children and older adults, who manifested a high rate of intrusion errors on the mixed Reading Span Test. A secondary finding was that the type of intrusions differed somewhat between children and older adults, the latter demonstrating more sensitivity to no-longer-relevant words (previous intrusions), whereas children produced a higher number of irrelevant words (extraneous intrusions). As a whole, the present data confirm that inhibitory efficiency in WM tasks, as assessed by the susceptibility to report irrelevant items, varies with age, and further suggest that the availability of attentional resources influences the efficiency of inhibition across the life span. More research is necessary to provide a full account of the changes that occur across the life span in susceptibility to interference in complex WM tasks such as the Reading Span Test.

AUTHOR NOTE

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NOTES

1. It should be noted that the same pattern of results was obtained when analyses were conducted on the raw number of intrusion errors.

2. To ensure that the respective age groups of both experiments were comparable in terms of age, education, Raven's scores, and Mill Hill's scores, *t* tests were performed. Furthermore, it is important to note that the pattern of data (i.e., the percentage of correctly recalled words and the rate of intrusions) of the subsample of participants in Experiment 1 was similar to that of the whole sample presented in Experiment 1.

3. Note that the decrease in proactive interference observed for the older adults cannot be attributed to the fact that fewer items (i.e., sentences) were presented in Experiment 2 than in Experiment 1. First, the number of items was nearly the same in both experiments, so the probability of producing one type of intrusion was similar. In Experiment 1, 56 items were presented. In Experiment 2, the number of items depended on each individual's span score. For example, an individual with a span of two (which corresponded to 38% of the older adults in Experiment 2) received 40 items in level n and 60 items in level $n+1$. Also, an individual with a span of three (29% of the older adults in Experiment 2) performed 60 items in level n and 80 items in level $n+1$. Second, we attempted to control for the different number of items presented to individuals by reporting the three types of errors relative to the number of correctly recalled words.

4. We thank anonymous reviewers for suggesting this interpretation.

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