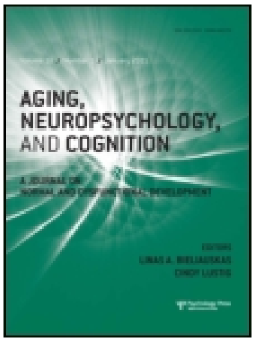

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Differential Age Effects in Load-Dependent Memory Processing

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ABSTRACT

This study examined differential age effects in a young and a middle-aged sample by means of a sequential *n*-back task with increasing memory load. Participants processed two streams of stimuli either separately as a single task, or simultaneously as a dual task. We investigated age effects as a function of memory load in both the single and the dual-task version. In accuracy, we observed differential age effects as a function of load, which were more prominent in the dual-compared to the single-task versions. That is, middle-aged participants performed poorer than young adults in the dual-task conditions, suggesting that early age-related changes become especially apparent in conditions where task coordination and resource sharing come into play. Regarding latencies, we observed no differential age effect, which we believe is due to characteristics of the sequential *n*-back task.

Keywords: Middle-aged; Working memory; *n*-Back; Dual task; Memory load.

INTRODUCTION

Performance decreases are common with aging in many cognitive domains, such as perceptual speed, memory, or fluid intelligence (Park et al., 2002). A parsimonious account for these results ascribes it to the decline of a general underlying resource or cognitive primitive, i.e., a basic attribute involved in a variety of higher cognitive functions (Hartley & Little, 1999; Luszcz & Bryan, 1999a, 1999b; Verhaeghen & Basak, 2005). Various attributes which mediate age-related performance declines have been identified, such as processing speed (Salthouse, 1996), attention (Salthouse, 1988), or working

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memory capacity (WMC; Oberauer & Kliegl, 2001; Park et al., 1996). In this study, we will focus on WMC as mediating factor of age-related performance decreases. WMC is usually defined as the limited amount of (separate) information units which an individual can hold in mind at a given moment in time in the face of distraction (e.g., Cowan et al., 2005). In line with the notion of being a general underlying process, WMC is related to a broad range of cognitive functions including reasoning and fluid intelligence (e.g., Kyllonen & Christal, 1990; Süss, Oberauer, Wittmann, Willhelm, & Schulze, 2002).

Interestingly, age-related differences seem to be more pronounced as the demands on WMC increase, which can be achieved by increasing the amount of memoranda (Oberauer & Kliegl, 2001). The demands on WMC can also be increased by using a dual-task procedure. It has been proposed that dual-task performance yields a relatively pure estimate of WMC, because the dual-task procedure prevents the use of task-related strategies that considerably contribute to performance in single tasks (Oberauer, Lange, & Engle, 2004). In general, dual tasks are assumed to place a heavy load of executive processing (Baddeley, 1996a; Oberauer et al., 2004; Salthouse & Miles, 2002) which is seen as especially prone to aging processes (Dempster, 1992). Indeed, dual tasking is a domain in which age-related declines are consistently observed, especially if the processing demands are high (Craik, 1977; Kramer & Larish, 1996). These findings have been interpreted from a general cognitive resource perspective, stating that in older adults, this resource is more limited. Thus, if the first task already requires a considerable amount of resources, there are fewer resources left to perform a secondary task (Hartley & Little, 1999). However, this conclusion has been criticized because of serious methodological problems in many studies (Hartley & Little, 1999; Logie, Della Sala, MacPherson, & Cooper, 2007; McDowd & Shaw, 2000; Salthouse, Fristoe, Lineweaver, & Coon, 1995): The performance of older and younger participants in the single tasks was often not equated for; thus, the older adults already performed worse than their young counterparts in the single task. Thus, it is difficult to say whether the dissociations between age groups in the dual tasks reflect deficits in the component tasks, or a specific dual-task deficit. Indeed there is evidence that when the difficulty in the primary task is equated for between-groups, the dual-task specific age-related differences become less reliable or even vanish (e.g., Hartley & Little, 1999; Somberg & Salthouse, 1982). Nonetheless, there are studies that reported differential age-related changes in dual-task conditions, even after equating single-task performance between-groups (e.g., Logie, Cocchini, Della Sala, & Baddeley, 2004; Logie et al., 2007; Salthouse, Rogan, & Prill, 1984).

Verhaeghen and Basak (2005) reasoned that age effects might be especially prominent if participants have to maintain (or retrieve) two task sets concurrently, which explains the dual-task specific deficits in the older adults. Verhaeghen and Basak (2005) propose that it is the shift of the focus of attention from one task set to another that is specifically prone to age-related changes. They confirmed this claim with an item-judgement task in which older adults performed worse in a task that demanded the shift of attention compared to a task where this shift was not required. More recently, Van Gerven, Meijer, and Jolles (2007) replicated this effect by comparing a middle-aged with a young participant group.

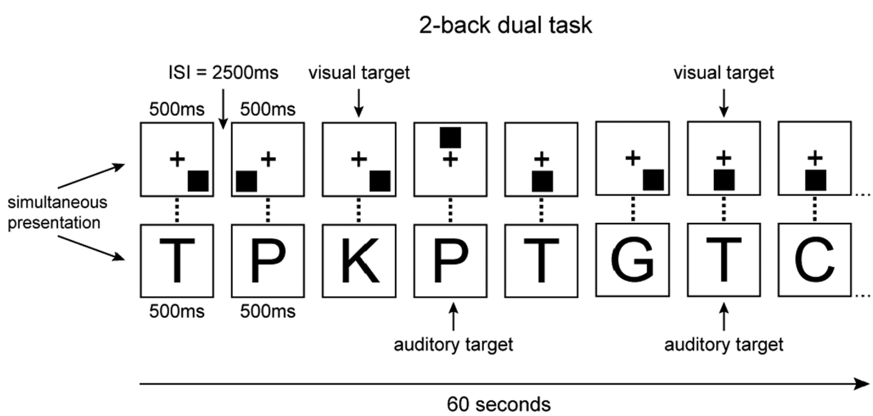
Alternatively, one can look at dual-task specific deficits in older adults from the perspective of the inhibitory framework as proposed by Hasher and Zacks (1988), stating that older adults suffer more from interference processes than younger adults. According to this theory, age-related differences are attributed to deficient inhibitory functions that can occur at three different stages, all of which require controlled processing (Lustig, Hasher, & Zacks, 2007): First, the control of the access to the focus of attention, second, the deletion of irrelevant information, and third, the suppression of strong, but inappropriate responses. Thus, in this view, it is not the WMC per se that is deficient in old adults, but its functionality, due to an inability in effectively inhibiting and controlling competing items that have to be processed.

In sum, it seems that age-related deficits occur if task demands are high, i.e., if the task requires a considerable amount of controlled processing (Oberauer & Kliegl, 2001; Verhaeghen & Cerella, 2002).

Another issue that is of interest in the context of aging and WMC is the assumption that WMC is not unitary. There is evidence for content-specific dissociations showing that visuospatial and verbal processes reflect separate components of WM (Baddeley, 1996b; Oberauer, Süss, Schulze, Wilhelm, & Wittmann, 2000) which is also supported by patient data (Vallar & Baddeley, 1984) and by the neuroimaging literature (Smith, Jonides, & Koeppe, 1996; Wager & Smith, 2003). In aging, although performance decreases are observed in both visuospatial and verbal domains, there may be an asymmetric change between the modalities. While some groups report a greater age-related decline in processing visuospatial than verbal material (e.g., Hale & Myerson, 1996; Jenkins, Myerson, Joerding, & Hale, 2000; Leonards, Ibanez, & Giannakopoulos, 2002; Myerson, Hale, Rhee, & Jenkins, 1999), there are others showing the opposite pattern (e.g., Fastenau, Denburg, & Abeles, 1996; Janowsky, Carper, & Kaye, 1996). Finally, there are studies in which no asymmetric age effects in modality are observed (e.g., Kemps & Newson, 2006; Park et al., 2002; Salthouse, 1995). In sum, the issue of a differential decline in visuospatial and verbal material with aging is not resolved.

The purpose of this study was to investigate several processes that might be affected by age-related changes. First, we looked at differential age effects in visuospatial and verbal domains in WMC. Second, we investigated load-dependent age-related effects by increasing the amount of memory load in general. Finally, we investigated whether load-dependent age-effects would be more pronounced in a dual-task condition than a single-task condition. To this end, we used a sequential *n*-back task which is frequently used in functional neuroimaging (e.g., Owen, McMillan, Laird, & Bullmore, 2005). This task requires participants to process a sequentially presented stream of stimuli and to respond whenever the current stimulus matches the one presented *n* items back in the sequence (see Figure 1). Memory load can be increased by increasing the value of *n*, which is expressed by a monotonic increase in error rates and reaction times (Jonides et al., 1997). In this task, storage and active manipulation processes are required (Smith & Jonides, 1997), therefore fitting well with WM conceptions emphasizing both storage *and* processing as defining characteristics (e.g., Baddeley, 1986; Cowan et al., 2005; Engle, Tuholski, Laughlin, & Conway, 1999). Some authors (Verhaeghen & Basak, 2005) have argued that the performance decrease from 1- to 2-back represents a qualitative difference between the two tasks: In the 1-back condition, the actual item that has to be processed is still in the focus of attention, whereas in the 2-back task, it has to be retrieved from outside and moved into the focus of attention in order to be processed. This attentional shift is expressed in the observed latency and error differences (Verhaeghen & Basak, 2005). This notion is in line with the assumption that the *n*-back task involves executive processing if $n > 1$ (Jaeggi et al., 2003; Oberauer, 2005; Smith & Jonides, 1997).

Figure 1. An exemplary 2-back condition of the *n*-back task, shown as the dual-task version where the auditory and visuospatial stimuli were presented simultaneously. Responses were required independently for each modality and had to be made whenever the current stimulus was the same as the one presented *n* positions back in the sequence. In the single task conditions, the stimuli were presented only in one modality. ISI, Interstimulus Interval (fixation cross).



The *n*-back task is sensitive to interindividual differences (Gevins & Smith, 2000; Hockey & Geffen, 2004; Jaeggi et al., 2007), and age-related changes (Leonards et al., 2002; Van Gerven et al., 2007; Verhaeghen & Basak, 2005), underlying its utility for the present study. In contrast to prior studies, we used the *n*-back task both in a single-task context and in a dual-task context with simultaneous visuospatial and verbal components. This is a procedure we have used before in young adults (Jaeggi et al., 2003, 2007; Jaeggi, Buschkuehl, Jonides, & Perrig, 2008).

For this study, we were especially interested in testing whether age-related differences would arise between young and middle-aged adults. We did not want to use an older sample because we suspected some aspects of the task to be too difficult. Further, people in their fifties are quite interesting in regard to WMC, because many of them are at a point in their lives when they are on their peak of performance at work, in social life, and in many aspects of cognitive functioning (Willis & Schaie, 1999), but nevertheless are at the edge of age-related declines. We assume that at this age, small performance declines could be compensated by the use of strategies. However, as we noted earlier, the use of strategies should less be applicable under dual-task conditions (Oberauer et al., 2004) and therefore, differences between young and a middle-aged participants should be most prominent under dual-task conditions at a high level of load.

Summary and Hypotheses

We used a sequential *n*-back task in four difficulty levels performed with stimuli from two modalities. Participants performed the task separately in each modality, but also as dual task version where the two streams were presented (and had to be processed) simultaneously. By means of this task we investigated the following hypotheses by comparing a young with a middle-aged sample:

First, we investigated whether there are differential age effects in visuospatial and verbal domains in WMC by looking at the *n*-back performance for each modality. Second, we expected to observe differential age effects in the sequential *n*-back task as a function of load, i.e., we hypothesized that the age-effect would be more expressed as the *n*-back load increased. Third, we expected that the age-related load effect would be more pronounced in the dual-task version of the task because of the increased processing load due to the additional processing demands, such as task-coordination. In combining these three factors that have an impact on working memory, the present study will try to look at their relative contributions to the age-related decline within one study. In general, we expected to observe age-related effects in accuracy but not in response latencies, because responses in the sequential *n*-back task were required at regular paces within a limited time window of 2500 ms.

METHOD

Participants

Thirty middle-aged (nine male; age range 50–64 years, mean age 55.6) and 30 younger participants (three male; age range 19–28 years, mean age 21.78) took part in the study. The sample of young adults consisted of undergraduate psychology students of the University of Bern who participated for partial fulfillment of course requirements. The middle-aged participants volunteered for the experiment and were recruited through the 'Volkshochschule Bern', a private institution for extension studies. All participants had normal or corrected-to-normal visual and auditory acuity, and no neurological disorders. Education level was comparable in both groups (i.e., college degree or higher), with a minimum of 12 years of education.

Apparatus and Material

The experiment was run on a personal computer with a 17 inch display (resolution 1024 × 768) using the software package E-Prime (Psychology Software Tools, Pittsburgh, PA). Participants' responses were registered with a PST Serial Response Box (Psychology Software Tools, Pittsburgh, PA).

We used visuospatial as well as auditory material as already used earlier (Jaeggi et al., 2007, 2008). The visuospatial stimuli consisted of blue squares appearing at one of eight different loci equally and symmetrically spaced around a constantly present white fixation cross in the center of a black screen. Assuming a monitor-to-eyes distance of 50 cm, the sides of the blue squares extended to a visual angle of 6.45°. Indicating the visual angle from the fixation cross to the center of each square, the positions of the eight loci were as follows[1]: –7.16°/6.13°; 0°/4.93; 7.16/6.13°; –6.54°/0°; 6.54°/0°; –7.16°/–6.13°; 0°/–4.93°; 7.16°/–6.13°. The verbal material comprised eight aurally presented German consonants (c, g, h, k, p, q, t, w) spoken by a female voice set at a comfortable volume adjusted for each subject individually. Locations and consonants were both chosen on the basis of their distinctiveness as assessed in pre-experiments.

Procedure

A sequential *n*-back paradigm was used with four levels of difficulty (0–3-back) with visuospatial and verbal material administered as single- and dual-tasks (see Figure 1). In the 0-back condition, participants were requested to respond whenever the current stimulus appeared at a pre-specified location

[1] A positive value indicates a location above or on the right side of the fixation cross and a negative value indicates a location below or on the left of the fixation cross.

(upper left) and/or if it consisted of a pre-specified consonant (‘q’). In the other *n*-back conditions, participants were requested to respond whenever the current stimulus was the same as *n* positions back in the sequence (*n* depending on the load level, i.e., 1, 2, or 3).

All stimuli were presented for 500 ms, followed by an interstimulus interval of 2500 ms (=1 trial) after which the next stimulus was presented. In the dual-task conditions, the verbal and visuospatial stimuli were presented simultaneously, and participants had to independently process each modality, whereas the task load was always the same for both modalities.

Participants performed three separate experimental blocks, a visuospatial, a verbal, and a dual-task block. Within each block, there were several runs consisting of only one type of *n*-back task which lasted 30 s (10 trials) for the 0-back task, and 60 s (20 trials) for the 1-, 2-, and 3-back tasks. Each *n*-back load level appeared twice (in a random order) and was always preceded and followed by the 0-back task. This procedure was chosen in order to give the participants the chance to relax between conditions of higher *n*-back load (see also Jaeggi et al., 2003, 2007; Rose & Ebmeier, 2006).

All runs were matched for the number of targets (33%) and non-targets (67%), as well as for distractors (i.e., 2-back targets in a 3-back run). The stimuli were arranged in a pseudo-randomized order, i.e., the position of the targets varied randomly in each sequence.

Participants were instructed to respond as quickly and accurately as possible. They were asked to press a specified button with their right index finger for targets in the auditory tasks, and another button with their left index finger for targets in the visuospatial tasks; no responses were required for non-targets. The same response allocation was used in the dual-task conditions, where the targets could occur in just one modality, in both modalities at the same time, or in none.

Each task was verbally explained to the participant, followed by a practice session. Half of the participants started the experiment with the visuospatial block and completed the verbal block after a break. The other half performed the single tasks in the reverse order. All participants finished with the dual-task block.

Data Acquisition

Participants’ performance, i.e., hits (responses to targets), false alarms (responses to non-targets) and the corresponding reaction times (RTs; for correct responses only) were recorded during a response window of 2500 ms starting with the stimulus onset time. For accuracy rates, we used the discrimination index (P_r) as proposed by Snodgrass and Corwin (1988) by subtracting the false alarm rate from the hit rate, which constitutes an estimate of true positive responses. For each condition and age group, we checked for statistical outliers being defined as ±3 *SD* from the mean. Outliers (<1% of all data points) were then replaced by that value. For RTs (hits only), we used median values instead of means which served as statistical outlier control.

Data analysis

We had a mixed 2 × 2 × 2 × 4 repeated-measures design with the factors age group (young vs. middle-aged), task (single vs. dual), modality (visuospatial vs. auditory), and *n*-back load (0–3-back). Analyses of variance (ANOVAs) were carried out separately for accuracy rates and RTs. Additionally, we conducted a qualitative analysis of speed-accuracy trade off measures as proposed by Verhaeghen, Steitz, Sliwinski, and Cerella (2003), since it seems that dual-task specific age effects can be explained in differential speed-accuracy trade-offs in different age groups.

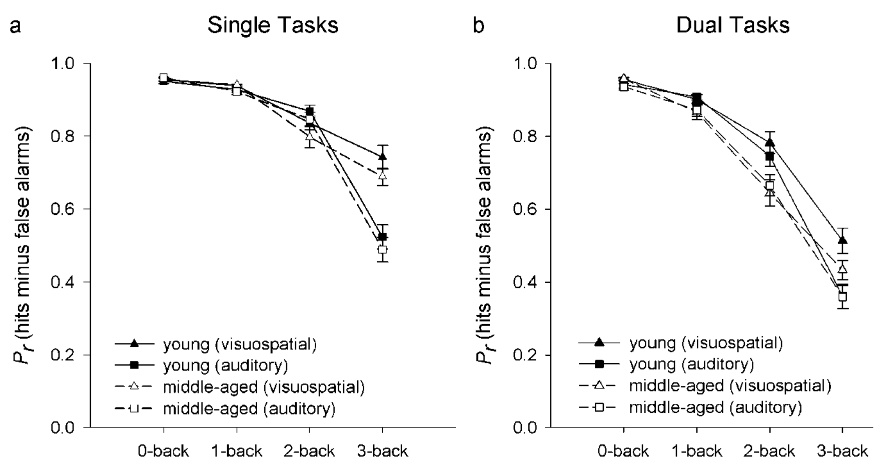
RESULTS

Accuracy

Descriptive measures for each age group and each load level are shown in Figure 2. Note that performance was above chance level ($P_r = 0$) for both age groups in all conditions, even for the 3-back task in the dual-task condition (*young*: $t(29) = 17.15$; $p < .001$; *middle-aged*: $t(29) = 18.90$; $p < .001$) although the mean performance was very low in both groups (*young*: $\bar{x} = 0.44$; *SD*: 0.14; *middle-aged*: $\bar{x} = 0.40$; *SD*: 0.11).

The four-way repeated measures ANOVA with task (single vs. dual), modality (visuospatial vs. verbal), and load (0–3-back) as within-subject

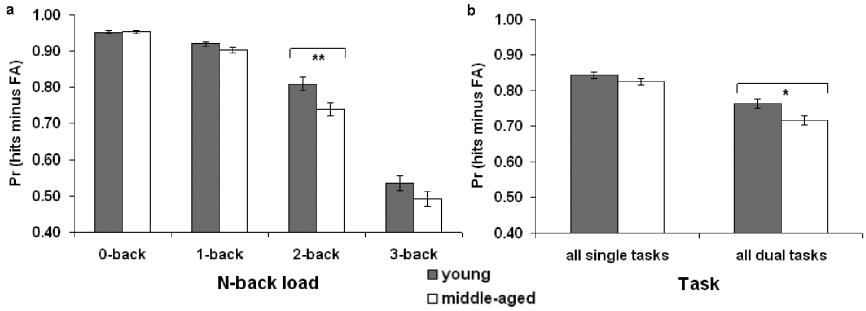
FIGURE 2. Means and standard errors of the mean for accuracy (P_r; hits minus false alarms) plotted separately for each age group and modality. (a) Single tasks; (b) dual tasks.



factors, and age-group (young vs. middle-aged) as a between-subject factor revealed significant main effects of modality ($F(1, 58) = 19.57$; $p < .001$; $\eta_p^2 = 0.25$) and load ($F(2.09, 174) = 534.61$; $p < .001$; $\eta_p^2 = 0.90$), as well as a significant modality × load interaction ($F(2.07, 174) = 40.07$; $p < .001$; $\eta_p^2 = 0.41$). In addition, there was a main effect of task ($F(1, 58) = 157.52$; $p < .001$; $\eta_p^2 = 0.73$), and a significant task × load interaction ($F(3.19, 174) = 45.48$; $p < .001$; $\eta_p^2 = 0.44$), and finally, a task × modality × load interaction ($F(2.00, 174) = 7.60$; $p = .001$; $\eta_p^2 = 0.12$). Specific pair-wise comparisons conducted post hoc and Bonferroni corrected for multiple comparisons showed that there were no significant differences in performance between modality, except in the single task at highest level of load (*3-back*: $p < .001$), and in the dual task at highest and lowest level of load (*3- and 0-back*: $p < .05$), for all of which the performance was better in the visuospatial task. The performance was consistently higher in the single task (all $p < .01$), except at easiest level of load (0-back), where there was no significant difference whether the task was performed as single or dual task. Finally, there were significant differences comparing each load level, for each modality, as well as for the single and dual tasks (all $p < .001$).

Regarding the hypothesized age-related effects, there was a significant main effect of age group ($F(1, 58) = 5.51$; $p < .05$; $\eta_p^2 = 0.09$), a significant load × age group interaction ($F(3, 174) = 3.31$; $p < .05$; $\eta_p^2 = 0.05$), as well as a trend for a task × age group interaction ($F(3, 174) = 3.51$; $p = .07$; $\eta_p^2 = 0.06$). In addition, the three-way interaction task × load × age group could be considered as trend ($F(3, 174) = 2.13$; $p = .098$; $\eta_p^2 = 0.03$). No other interactions reached significance. *Post-hoc* tests (two-tailed; Bonferroni corrected) revealed that the middle-aged group performed significantly worse than the young participants at 2-back load only ($t(58) = 2.75$; $p < .01$; see Figure 3a), but also, that the overall dual-task performance was significantly lower in the middle-aged group than in the young group ($t(58) = 2.58$; $p < .05$), whereas

FIGURE 3. Means and standard errors of the mean for (a) the load × age group interaction, and (b) the task × age group interaction as obtained by the four-way ANOVA. *$p < .05$; **$p < .01$.



the single-task performance was not significantly different between-groups (see Figure 3b). Although the three-way interaction was not significant, a closer inspection nevertheless suggested that the age-related difference was mainly driven by the effects in the dual tasks, especially at intermediate level of load, rather than by the single task in which the performance of the two age groups was comparable (*dual 1-back task*: $t(58) = 1.81$; $p = .08$; *dual 2-back task*: $t(58) = 2.92$; $p < .01$; all other comparisons: $t < 1.3$).

Thus, since the four-way ANOVA did not yield conclusive results in regard to our hypotheses as there were only trends for the task × age group and the task × load × age group interactions, we performed additional three-way ANOVAs for the single and dual tasks separately, in order to obtain a clearer impression on the matter:

Single Tasks

A 2 (modality) × 4 (load) × 2 (age-group) ANOVA revealed significant main effects of modality ($F(1, 58) = 18.98$; $p < .001$; $\eta_p^2 = 0.25$) and load ($F(1.63, 174) = 275.56$; $p < .001$; $\eta_p^2 = 0.83$), and a significant modality × load interaction ($F(2, 174) = 47.54$; $p < .001$; $\eta_p^2 = 0.54$). *Post-hoc* tests (two-tailed; Bonferroni corrected) showed that the accuracy rates decreased with increasing *n*-back load, but that this decrease was more pronounced in the auditory conditions at high load levels as there was a significant difference at the 3-back level ($t(59) = 8.19$; $p < .001$). However, there was no significant main effect for age group and no interaction involving age group as a factor reached significance (all $F < 2$).

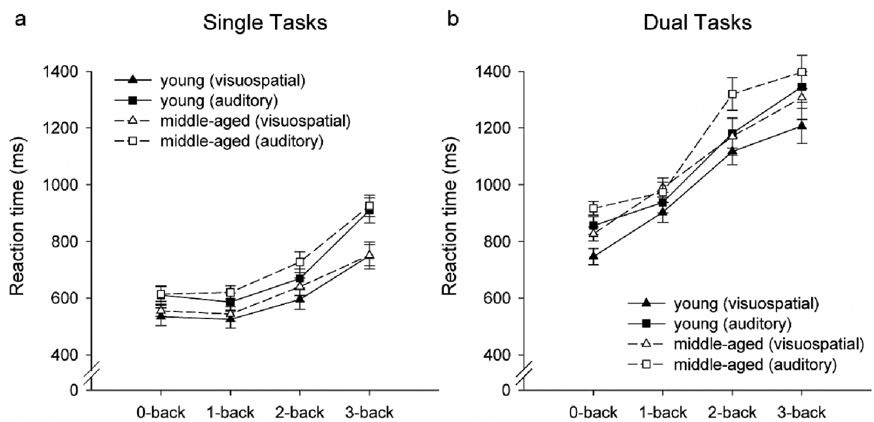
Dual Tasks

The three-way ANOVA again revealed significant main effects of modality ($F(1, 58) = 7.90$; $p < .01$; $\eta_p^2 = 0.12$) and load ($F(2.41, 174) = 422.06$; $p < .001$; $\eta_p^2 = 0.88$), and a significant modality × load interaction ($F(2.08, 174) = 8.40$; $p < .001$; $\eta_p^2 = 0.13$). *Post-hoc* tests (two-tailed; corrected) showed that accuracy rates were again lower in the auditory conditions with significant differences in the 0-back ($t(59) = 3.37$; $p < .01$) and the 3-back condition ($t(59) = 3.61$; $p < .01$). In contrast to the single-task analyses, we observed a significant main effect of age group ($F(1, 58) = 6.59$; $p < .05$; $\eta_p^2 = 0.10$), and a significant load × age group interaction ($F(3, 174) = 3.75$; $p < .05$; $\eta_p^2 = 0.06$). *Post-hoc* analyses (two-tailed; Bonferroni corrected) revealed that the middle-aged group performed worse than the young participants, but only at intermediate levels of load (2-back; $t(58) = 2.91$; $p < .05$). No other interactions were significant (all $F < 2$).

Reaction Times

Descriptive measures for each age group, modality and load level are shown in Figure 4.

FIGURE 4. Means and standard errors of the mean for reaction times (hits only) plotted separately for each age group and modality. (a) Single tasks; (b) dual tasks.



The four-way repeated measures ANOVA (task × modality × load × age group) revealed significant main effects of modality ($F(1, 56^2) = 57.16$; $p < .001$; $\eta_p^2 = 0.51$) and load ($F(1.79, 168) = 142.31$; $p < .001$; $\eta_p^2 = 0.72$), as well as a significant modality × load interaction ($F(1.92, 168) = 5.34$; $p < .01$; $\eta_p^2 = 0.09$). Additionally, there was a main effect of task ($F(1, 56) = 470.35$; $p < .001$; $\eta_p^2 = 0.89$) and a significant task × load interaction ($F(2.35, 168) = 37.01$; $p < .001$; $\eta_p^2 = 0.40$). Also, there was a borderline three-way task × modality × load interaction ($F(2.27, 168) = 2.76$; $p = .06$; $\eta_p^2 = 0.05$). *Post-hoc* tests (two-tailed; Bonferroni corrected) revealed that in general, latencies were longer in response to the auditory targets compared to the visual targets at all levels of load (all $p < .01$) and longer in the dual tasks compared to the single tasks at all levels of load (all $p < .001$). However, the modality differences were mainly observed in the single tasks (all $p < .05$), whereas in the dual tasks, the modality difference was only significant at easiest level of load (0-back; $p < .01$). Further, in the single tasks, there was a monotonic increase in RTs in both modalities as expressed by significant differences between each load level (all $p < .01$), except at easiest level of load, i.e., for the 0- vs. 1-back comparison ($p = ns$). In contrast, in the dual tasks, there was a significant difference between all load levels in both modalities, even at lowest levels of load (all $p < 001$); however, there was only a marginal increase in latencies from 2- to 3-back (visuospatial 2-vs. 3-back: $p = .06$; auditory 2- vs. 3-back: $p = .08$). There was no main

[2] Since only RTs in regard to hits were taken into account, there was one participant in each age group without any hit at conditions of higher load in the dual task, thus, resulting in the smaller df.

effect of age group and no other interactions involving age group as a factor reached significance (all $F < 1.5$).

Note that we used non-transformed RT measures for our analyses above. However, the analyses conducted with logarithmic transformed RTs as suggested by some authors (Cerella, 1990; Verhaeghen & Basak, 2005) yielded the same result patterns as described above, i.e., no differential age-related effects.

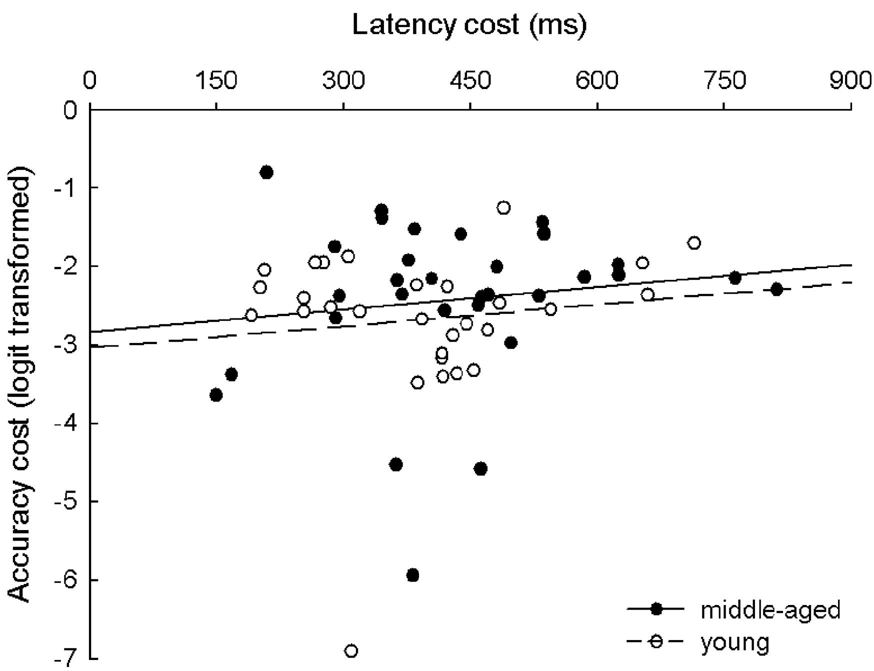
Speed-accuracy trade-off Measures

In order to investigate whether the observed differential group effects could be attributed to strategy-related processes, i.e., to differential speed-accuracy trade-off strategies, we conducted a qualitative analysis as proposed by Verhaeghen et al. (2003) by looking at dual-task costs: We plotted logit-transformed accuracy costs (dual- minus single-task; logit = $\ln[P/(1–P)]$; P = proportion correct) as a function of latency costs (dual- minus single-task; mean all load levels) separately for each age group (see Figure 4). The logit (i.e., the natural logarithm of an odds ratio)-transformation was used because there were near ceiling performance in the 0- and 1-back tasks in some participants. Further, this approach is seen as an appropriate way to model proportions in linear models which also eliminates eventual problems with heteroscedasticity (McCullagh & Nelder, 1989; Peng, Lee, & Ingersoll, 2002; Verhaeghen et al., 2003). In regard to the plot on Figure 5, an informal inspection of the plot suggests that in contrast to Verhaeghen's participants, our two age groups do not differ much from each other. This conclusion is also supported by looking at the comparable regression lines, drawn separately for each age group, which remained similar even after removing an outlier in the young participant group. Further, compared to the study by Verhaeghen et al. (2003), our participants showed less of a speed-accuracy trade-off in general. This can be inferred from the clustering in the center of the figure rather than along one of the axes, and also, by the almost non-existent slope of the regression lines, suggesting that the dual-task costs occur in both accuracy *and* latency, rather than just in one of them. Finally, participants from both age groups seemed to have followed the instructions not to sacrifice speed or accuracy to keep up the other.

DISCUSSION

In the present study, we investigated age-related effects using an *n*-back task in two modalities and with four levels of difficulty in single and dual-task conditions. First, we were interested in whether there are differential age effects in visuospatial and verbal domains in WMC by comparing the *n*-back performance for each modality. In general, our results indicate that there is an advantage for the processing of the visuospatial material

FIGURE 5. Dual-task costs in logit-transformed accuracy as a function of dual-task costs in latency (absolute values) plotted separately for each age group (cf. Verhaeghen et al., 2003). The regression lines represent the curve fit for each age group separately (*young*: R^2 = .016; *b1* = 0.001; *middle-aged*: R^2 = .017; *b1* = 0.001).



compared to the auditory-verbal material, which was observed in both accuracy and latencies. This advantage might have resulted because of rehearsal processes, present in the auditory-verbal condition, but not in the visuospatial condition. Indeed, post-test interviews in an earlier study revealed that participants rehearse the auditory-verbal material but use a visual tracking strategy for the visuospatial material, a strategy which seems to be faster and more efficient (Jaeggi et al., 2007). For the auditory-verbal task, the higher the level of load, the more items have to be backtracked and rehearsed, thus, taking more time as the level of *n* increases. This interpretation could explain why the modality difference is larger at higher levels of *n*. Note that the observed modality-specific effects were the same for the young and the middle-aged participants, thus, with this paradigm, there seem to be no apparent processing differences between those two age groups. This finding suggests that age-related decline does not affect one domain to more than the other, in line with other studies of recognition performance, which did not find domain-specific age effects either (Kemps & Newson, 2006; Park & Schwarz, 2000).

Second, we expected to observe differential age effects in the sequential *n*-back task as a function of load, i.e., we hypothesized that the age-effect would be more expressed with increasing *n*. This hypothesis proved to be only partially confirmed: Although there was a significant load × age group interaction, the difference between groups was only significant at 2-back, but not as predicted, at the most difficult 3-back level. The most parsimonious approach to explain this finding would be to assume that the 3-back level was too difficult for both age groups by reaching a general capacity limit. Such an explanation would be in line with McElree (2001) stating that three items are too many to be reliably kept in the focus of attention. Thus, this increased error variance might have masked differential age effects.

Third, we hypothesized that the age-related load effect would be more prominent in the dual-task version: Indeed, although there was only a trend for a task × age group interaction, the *post-hoc* tests as well as the additional three-way ANOVAs clearly showed that the differential age-effect was only reliable if the task was performed as a dual task. We suggest that this age-related effect primarily resulted from the additional processing load provided by the dual-task situation, i.e., the time sharing and task coordination. Whereas the middle-aged participants are able to keep up with processing load as long as they can concentrate on one modality stream, they reach their capacity limits if they have to simultaneously process two information streams.

It can not be argued that the age difference in the dual-task conditions resulted from an age difference already present in the single task conditions, because there were no significant differences between age groups in any of the single task conditions. In addition, it seems that there is no apparent difference in terms of differential speed-accuracy trade off strategies between the two groups speaking to differential processing rather than a strategic difference between the two age groups.

How can we now merge the two different interpretations, one stating that there is a capacity limit of three items and one stating that age-related deficits are more prominent in situations requiring task coordination? Obviously, participants have to memorize twice as many items in the dual-task version as in the single task. That is, in the dual 2-back version, participants actually have to keep four items in memory. Moreover, in the dual-task situation, participants have to coordinate and combine the encoding, storage and retrieval of the two modality streams, sharing resources between those streams. Most probably, some of these shared processes are bottlenecked, resulting in lower performance in the dual task compared to the single task. Unfortunately, with the current outline of the task, we are not able to determine whether the bottleneck appears at encoding, storage, or retrieval/response, an issue which has been recently addressed by other authors (Logie et al., 2007). It seems though that participants are able to handle bottlenecks in a flexible way, depending on task demands (e.g., Meyer et al., 1995). In any case, it seems that young participants are better able to keep two items/chunks in mind, but have similar difficulties as older adults if the task goes beyond these two items. However, compared to the younger participants, older participants seem to have trouble in combining two items when they are present in modality streams in the dual-task situation.

Alternatively, it could also be that the amount of interference processes, either on the encoding, retrieval, or response level are significantly increased as the task is done as dual task, as predicted by the inhibitory deficit theory (Lustig et al., 2007). Although we can not disentangle the stage at which the interference is most detrimental, our results are in line with the theory. One major claim of the theory is that older adults have problems down-regulating currently irrelevant information, i.e., rejecting distracting items. We would predict false alarm rates (distractions or inappropriate responses), to track age-related differences. Although participants made less than 5% false alarms, older adults made more than twice (63%) the amount of false alarms than young participants ($F(2, 58) = 10.68$; $p < .01$; $\eta_p^2 = 0.16$). Therefore, it seems that older adults have more difficulties in discriminating correct from false responses, a finding which has also been frequently shown in recognition memory (e.g., Snodgrass & Corwin, 1988).

To conclude, it is difficult to estimate whether the age-related differences we found here can be attributed primarily to the lack of task coordination or to inhibitory control, which is one of the caveats of the present study. In any case, the proposition that age-related deficits especially show up if participants have to maintain more than one task set (Verhaeghen & Basak, 2005) fits nicely with our finding of dual-task specific differences.

In addition to time sharing and interference processing, the speed of processing might also contribute to the age-related differences in the dual task. Although we did not observe differences in reaction times, it could be that middle-aged participants need more time to rehearse or retrieve. This may exponentially show up in the dual-task, resulting in the larger amount of misses, whereas middle-aged participants are able to compensate such slowing in the single task by the use of modality-specific strategies. However, looking at RTs only, we did not find any age-related differences. This is consistent with other studies of the *n*-back task, showing age differences in accuracy only, but not in RT (Verhaeghen & Basak, 2005). The only significant age-related difference was observed in the visuospatial 0-back condition in the dual task ($t(58) = -2.10$; $p < .05$; two-tailed; uncorrected), where the middle-aged group performed more slowly (see Figure 3). Although hypothesized, this finding stands in contrast to many reports of general slowing in the aging literature and thus requires further explanation: First of all, because there is high variability in the younger group, there may have been a lack of power. However, a *post-hoc* power analysis (G*Power 3; Faul, Erdfelder, Lang, & Buchner, 2007) showed that although the achieved power for the main effect of age group was not very high in the single tasks ($1–\beta = .61$), it was large enough in the dual tasks ($1–\beta = .99$). Thus, the lack of power is not an exhaustive explanation for the absent group differences regarding RT. Rather, we assume that the lack of age effect in RT is related to our experimental design. The task was sequential and responses were required at regular paces within a limited time window of 2500 ms after which the next stimulus was presented. If participants did not have pressure to respond quickly, older participants may have taken a longer time to respond and thus the speed-accuracy trade-off might have changed, revealing group differences in response latencies. Related to this interpretation, there is evidence that age-related latency differences are dramatically reduced if the items in a digit symbol task are presented one at a time (Lustig, Hasher, & Tonev, 2006). The authors argue that this reduction is due a smaller amount of interference produced by the non-standard task execution. Therefore, as we had middle-aged and not old participants and a sequential paradigm, subtle differences in speed might have vanished.

Another related issue arises when looking at the general load-dependent increase in RTs that we observed in both age groups. In contrast, Verhaeghen and Basak (2005) reported no further increase in RT after $n > 1$. As pointed out by Verhaeghen and Basak (2005), constant RTs after $n > 1$ reflect a capacity limit, which is set at one item (see also McElree, 2001; Oberauer, 2002). As mentioned earlier, Verhaeghen and Basak (2005) argue that the increase in RT from 1- to 2-back represents a cost that is associated with the switching the focus of attention within WM. From that viewpoint, it seems odd that we had such strong load-dependent effects even after $n > 2$. How can we explain these different results? The most obvious difference between our study and the Verhaeghen study lies in the applied paradigm itself: Although introduced as *n*-back task, Verhaeghen's task seems to be quite different from a 'classical' *n*-back task in memory load requirements, which is also expressed by considerably higher accuracy measures compared to ours. The main difference in their task is that they provided participants with temporal and positional cues by displaying the stimuli row by row in *n* columns (representing the value of *n*). In their task, each column was assigned to a different color, and each stimulus had to be compared to the stimulus that was previously presented in the same column, one row above. One could argue that the main task in Verhaeghen's study was an identity judgement – the temporal order is provided by the color and the organization in rows. Thus, comparing a 2- with a 5-back task, it is only the number of rows that increases, but the essential matching process itself remains the same. From this perspective, it makes sense that there is no difference in RT, however, the decrease in accuracy shows up due to the increased number of items in the rows, because there are more interference and/or decay processes. Indeed, there is evidence from the literature for that interpretation. For example, McElree (2001) hypothesized that there would be no RT-differences in different *n*-back levels if 'the position of the item in the *n*-back tasks was explicitly coded and stored' (p. 829). His reasoning is that the retrieval of item information occurs very fast and by a 'direct-access mechanism' (McElree, 2001; McElree & Dosher, 1989), whereas the retrieval of temporal and positional order information appears to happen more slowly and search-like (McElree & Dosher, 1993). Thus, if the temporal and positional order is provided by external cues such as in Verhaeghen and Basak's study, item-retrieval seems to be the same for the different levels of *n*, resulting in the comparable RT.

On the other hand, in the classical *n*-back task, there are no external cues which provide information regarding position or temporal order, thus, in addition to the identity judgement, the sequence and its order has to be monitored, maintained and updated by the subject itself. Therefore, for each item, participants have to simultaneously store *n* items in memory, update its string, i.e., discard the one farthest back, and match it to the one that is actually presented. In addition, they constantly have cycle *n*-positions back in the sequence and compare a previous item with the current item; a process which takes longer as the value of *n* increases, resulting in monotonic RT-increases. Consequently, the RT naturally increases from 2- to 3-back. Indeed, this pattern is frequently reported by using various stimulus materials (e.g., Bliss & Hamalainen, 2005; Braver et al., 1997; Ellis, Mehta, Wesnes, Armstrong, & Nathan, 2005; Jonides et al., 1997; Koivisto, Krause, Revonsuo, Laine, & Hamalainen, 2000; Martinkauppi, Rama, Aronen, Korvenoja, & Carlson, 2000; McEvoy, Smith, & Gevins, 1998; Nystrom et al., 2000; Pesonen, Hamalainen, & Krause, 2007; Rose, Simonotto, & Ebmeier, 2006; Watter, Geffen, & Geffen, 2001), and our lab yielded comparable results using the exact same procedure as described in the present study (Jaeggi et al., 2007), in addition to two other studies using a considerable sample size (Jaeggi, 2005; $N = 132$ and $N = 50$).

Still, there are some studies that show the aforementioned asymptotic level in RT after $n > 2$ (Caseras et al., 2006; Harvey et al., 2005; Hockey & Geffen, 2004; Honey et al., 2002; Mattay et al., 2006; Sweet, Rao, Primeau, Durgerian, & Cohen, 2006), although in two of these studies, there is a slight increase from 2- to 3-back (Hockey & Geffen, 2004; Sweet et al., 2006). By evaluating the different paradigm-features used in those studies, it seems that the duration of the ISI and therefore the response window plays a crucial role for the emerging RT pattern: the shorter it is, i.e., the more speeded the response, the smaller the difference between the 2- and the 3-back level in terms of RT. In those studies without difference between 2- and 3-back (Caseras et al., 2006; Harvey et al., 2005; Honey et al., 2002; Mattay et al., 2006), the ISI and/or response window is 2 s or less, whereas in all other studies, it is >2000 ms, typically 2500 ms as in the present study. Thus, one could hypothesize that if the task were self-paced, i.e., if the stimulus stays on-screen until the participant responds, reaction times would continue to increase with increased load. If the participant needs a longer time to cycle back through the memoranda due to higher *n*-back load, the response time in a 3-back task should be disproportionally longer than a 2-back task. Indeed, there is a recent study (Pesonen, Hamalainen, & Krause, 2007) which adopted that procedure, and their results exactly fit in this conclusion: the increase from 2- to 3-back was more than 500 ms, in contrast to the increase from 1- to 2-back, which was only 318 ms. As mentioned earlier, this interpretation is also in line with our results that we did not find any differential age-effects in RT, due to the restricted response window.

To summarize, our results show that there are no asymmetric modality-specific differences between age groups, however there is a general advantage for the processing of visuospatial compared to verbal material. Further, there are load-dependent age-effects, which are most prominent at a load-level of 2, which we interpret as a general capacity limit at a load-level 3 that might have masked age-related effects. Finally, we observed no age-related differences in the *n*-back single-task version in either accuracy or latency. This finding indicates either that the processes involved in the *n*-back single-task version (e.g., monitoring, updating, rehearsal storage, recognition) are comparable in young and middle-aged participants, or that the middle-aged could compensate any deficits by using strategies. However, in conditions with high processing demands, that is, in the dual task conditions where task coordination, resource sharing and interference processes come into play, age-dependent performance-declines become evident.

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