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Original Article

Cardiovascular Costs of Working Memory Performance: Effects of Age and Performance Feedback

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Abstract: Ageing is associated with impaired working memory (WM) performance that may increase cardiovascular costs in older workers. Performance feedback (FB) was assumed to compensate for performance decline and reduce cardiovascular costs. Forty-eight younger (29 ± 3 yr) and 45 older (55 ± 4 yr) healthy workers had to perform a 0-back task (low WM load), 2-back task (high WM load) and 2-back task with FB (high WM load & FB). Age-related performance decline and enhanced blood pressure (BP) reactivity to WM load were found. The baroreflex sensitivity (BRS) decreased under high WM load in older workers compared to younger workers. The FB abolished age differences in omission rate and increased low frequency heart rate variability (HRV) in both age groups. Moreover, FB reduced heart rate in older workers and increased BRS as well as high frequency HRV in younger workers. The results suggest that older workers compensate for WM performance decline at cost of heightened BP due to age-related reductions of vagal tone and impairments of the baroreflex mechanism. The performance FB helps older workers to partly compensate for performance deficits and reduce cardiovascular costs by moderate decreases in sympathetic tone.

Key words: Elderly workers, Working memory, Feedback, Baroreflex, Blood pressure, Heart rate

Introduction

Working memory (WM) has been considered as the system where the action-related information is continuously retrieved from long-term memory, temporarily stored and updated until the action is completed[1)]. This mental buffer is essential for flexible action regulation and adjustment to environmental demands. WM performance worsens with advanced age probably due to progressive loss of neurons in the structures underlying WM e.g. dorsolateral prefrontal cortex and hippocampus[2)]. This parallels the body of research showing an age-related activation of additional brain areas (e.g. dorsolateral prefrontal cortex) which is accompanied by a moderate increase in WM performance, see e.g.[3)]. This effect has been interpreted as compensatory effort and re-allocation of processing resources to prevent performance decline in older adults. However, the compensatory activation may require a heightened level of metabolic support which, in turn, may elevate cardiovascular costs in terms of increases in blood pressure (BP) reactivity to cognitive challenge which is indicative of long-term cardiovascular risks[4, 5)]. Age-related changes in WM performance and cardiovascular reactivity have been usually investigated in samples comprising non-employed people like young students or retirees[6–11)]. Hence, the re-

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sults cannot directly be implicated for assessment of cognitive declines and cardiovascular risks in older workers. In addition, it is not clear whether moderate impairments in WM performance and enhanced cardiovascular costs can also be seen in middle-aged workers (about 55 yr old) who are about 10 to 15 yr younger than those participating in the majority of ageing studies.

According to the "doctrine of autonomic space"[12], the adaptation to mental challenge may be achieved by various interactions between sympathetic and parasympathetic (vagal) cardiac control. Hence, the relationship between measures reflecting the influences of both branches of autonomic nervous system may also differ between age groups. However, aging studies have usually been focussed on age-related changes in single cardiovascular parameters like BP as a function of mental load while the relationship between various measures and their reactivity within younger and older groups have rarely been discussed (see[5] for review). Some authors showed that maintenance of information in memory induces greater heart rate (HR) acceleration in older adults than in younger adults[6]. Other authors did not find an enhanced HR reactivity in older people when an intense emotional load was applied[8]. It is probably due to the fact that HR is regulated by both sympathetic and vagal pathways[13] which are highly susceptible to aging[14]. In a previous study we found that HR in the older group was more affected by sympathetic tone while in the younger group HR was associated with vagal influence[15]. Taken together, the results suggest that HR is only to a limited extent reliable to assess age effects on cardiovascular reactivity to WM load. By contrast, the heart rate variability (HRV) is considered as a reliable index for cardiovascular adaptation to task requirements[13]. The age-related decrease of HRV is a robust finding which has been attributed to impaired vagal control over the cardiovascular system in older people[14].

The systolic and diastolic blood pressure (SBP, DBP) reactivity to laboratory stressors is usually greater in older than in younger adults and is thought to be a marker of age-related sympathetic predominance that usually goes along with vagal withdrawal[5]. By contrast, younger people meet task demands by vagal withdrawal only while sympathetic tone (and hence SBP) remains constant during the experiment[15]. One of the most important mechanisms providing the maintenance of adequate BP in the cardiovascular system is the baroreflex[16]. The baroreflex sensitivity (BRS) reflects the magnitude of change in heart period (e.g. HR^{-1}) relative to change in SBP. The greater the BRS is the quicker and more effective the cardiovascular system can adapt to changing task demands. The age-related reduction of the baroreflex may contribute to permanently elevated BP in older people[17]. However, the role of the baroreflex in age-related increases of cardiovascular costs under WM load is not yet fully understood.

In the present study we first aimed at replication of our previous data[15] in a larger sample of workers. As both SBP and DBP are susceptible to age[4, 5], it appears conceivable to obtain age effects on both measures. In our previous study the age differences in DBP reactivity did not reach significance probably due to a small sample size. There are also data that age differences in SBP reactivity are more consistent than those in DBP reactivity while the mechanisms underlying this discrepancy have not been discussed[18].

The second aim of the study was to examine the role of the baroreflex in cardiovascular adaptation to WM demands. The weakening of the baroreflex in older workers would enhance cardiovascular costs in terms of increases in sympathetic tone (enhanced BP) and vagal withdrawal (reduced HRV) during WM load and recovery period. By contrast, younger workers would have a more efficient baroreflex mechanism that reduces cardiovascular costs. Hence, in younger adults, vagal withdrawal (reduced HRV) and constant sympathetic tone (constant BP) under high WM load would be expected. Hence, it was assumed that younger and older people meet task requirements by different constellations of sympathetic and vagal systems.

The findings on age-related WM decline have usually been obtained in healthy retired people[7, 11]. This complicates the generalisation of results to the population of older employees as the employment is thought to stimulate cognitive functioning in older people[19]. The third aim of the study was to examine to what extent the WM decline can also be observed in middle-aged workers.

Finally, we investigated whether a performance feedback (FB) may mitigate age-related WM impairments and concomitant cardiovascular costs. The n-back task used in the previous study[15] was extended with a FB condition that should help participants to reduce WM load, improve their performance and decrease cardiovascular costs. In the low WM load condition participants had to respond to the letter "X" as quickly as possible while in the high WM load condition participants had to respond when the letter was identical to the letter two trials previously. In the high WM load & FB condition participants used an acoustic FB to reduce WM load. The FB was assumed to be especially helpful for older participants who tend to rely on external information to compensate for memory

Table 1. Characteristics of the participants

	Younger		Older		*t*-Test	
	mean	StD	mean	StD	*t*	*p*
n	48		45			
Age, yr	28.9	3.49	55.27	3.83		
Age range, yr	21–35		51–65			
% women	50		53			
% college/university graduates	33		69			
% office workers	54		60			
% non-office workers (workman, policeman, nurse, sport coach etc.)	40		22			
% executives	6		18			
% smokers	40		32			
cigarettes per day	3.26	5.47	3.62	7.32	–0.25	0.79
Pulse (beat/min)	70.75	10.54	68.25	14.68	–0.60	0.54
Diastolic BP (mmHg)	72.12	9.42	73.77	15.55	–0.57	0.57
Systolic BP (mmHg)	119.04	13.70	121.36	23.38	0.90	0.37
Body-Mass Index	23.37	3.85	24.51	3.96	–1.26	0.21

deficits[20)]. Therefore, the performance improvement and reduction of cardiovascular costs in the FB condition was expected. Despite the majority of experiments showed facilitating FB effects on performance, see[21)] for review, older adults may have problems with FB utilisation and do not always demonstrate performance improvements in the FB condition[22)]. To our knowledge, the present study is the first one that examined FB effects on WM performance and cardiovascular costs in younger and older workers.

Subjects and Methods

Participants

Forty-eight healthy younger workers and 45 healthy older workers were recruited through advertisements in local newspapers and public transport. The sample characteristics are presented in Table 1. The older and younger groups were matched for gender and smoking.

The participants had professional school qualifications or a college/university degree. Health complaints were checked in a pre-selection phone interview by a WAI questionnaire[23)]. Education level, current occupation, position, main work activities and their duration within a working day were assessed by a questionnaire. The exclusion criteria were cardiovascular, neurological or psychiatric disorders, head injury, use of psychoactive medications or β-blockers. Participants who have a daily consumption of more than 20 cigarettes, more than one litre of coffee as well as excessive alcohol consumption (more than 500 ml of beer or 200 ml of dry wine per day) were also excluded. Only participants who met the above criteria, had at least six months of work experience and were currently employed with at least 20 h per week were invited to a pre-selection session, see Procedure. All participants were right-handed, native German speakers, had normal or corrected to normal vision, gave an informed consent and were paid € 10 per hour for their participation. The experiment was approved by a local ethics committee.

Task

Twenty five 12 × 18 mm different Latin letters were presented successively in white on the black background for 200 ms with an inter-stimulus interval of 1,500 ms and a response window of max 1,500 ms; each of them appeared with equal probability and was randomly distributed along the trial sequence. In the 0-back task participants had to press a key with the right index finger when the letter "X" was displayed (low WM load). In the 2-back task (high WM load) they had to maintain all incoming stimuli in memory and press a key if a letter was identical to the letter presented two trials previously. In the 2-back & feedback task (high WM load & FB) an acoustic FB (a 50 ms tone) signalled correct responses (1000 Hz), omissions (2000 Hz) or false alarms (500 Hz). During a pre-selection session participants practiced to use the FB to cut a long sequence of stimuli into short target-to-target sub-sequences. The 1000 Hz and 2000 Hz tones signalled that participants do not need to maintain previous information and could completely focus on a next sub-sequence of 3 to 6 stimuli which included a target. The 500 Hz tone signalled that a target will come in 1 to 5 upcoming stimuli and participants were instructed to focus on these stimuli only. The low WM load condition consisted of 189 trials while the high WM load block and the high WM load & FB block consisted of 388 trials. The target probability (20%), physical and temporal features of tasks did not differ between conditions to avoid confusion with the WM load effect. The targets were quasi-randomly distributed across the trial sequence so that minimal two and maximal five non-targets were presented between targets. Different letters were used in a target-to-target sub-sequence and not repeated in the neighbour target-to-target sub-sequence. Hereby we prevented the lures in both 2-back blocks and consequently incorrect responses due to the interference with a neighbour letter and/or a letter from a neighbour sub-sequence.

Cardiovascular measures

Electrocardiogram (ECG) was taken throughout the experiment with the "Suempathy-100" system (Suess Medizintechnik LTD, Germany). Beat-to-beat BP was continuously registered from the left middle finger using a Finapres device (Ohmeda, USA). This technique does not allow a reliable estimation of absolute BP values and has been used for assessing relative BP changes against baseline. ECG and BP artefacts were corrected offline. HRV in the low frequency domain (0.04–0.14 Hz), LF-HRV thereafter, and high frequency domain (0.15–0.4 Hz), HF-HRV thereafter, as well as BRS were computed offline by the trigonometric regressive spectral analysis[24)] which allows a reliable HRV and BRS assessment already for short (30 s) data segments[25)]. Cardiovascular variables were measured in task blocks as well as during 90 s baseline and 90 s recovery period. Values were computed for each 5 s in the middle of a 30 s period which was shifted from zero until the end of the measurement in 5 s steps. This shifting window procedure revealed 13 data points for the baseline and recovery and up to 86 data points for the task blocks.

Procedure

In the pre-selection session participants took part in a general health check and then practiced in the 0-back task, 2-back task, and 2-back & FB task until they attained 90% correct responses. Arterial blood pressure at rest was measured via brachial cuff before, in the middle and at the end of the pre-selection session to exclude hypotensive or hypertensive individuals. The main experiment was conducted within one week after the pre-selection session. The experiment started between 9 a.m. and 10 a.m. and finished approximately between 11 a.m. and 12 noon while a 15 min. break was given in the middle of the experiment. Participants filled in questionnaires on detailed job characteristics, health status, sleep quality, and consumption of medications. Participants were requested to take a usual breakfast but refrain from consuming caffeinated beverages or alcohol on the day of the experiment. As soon as electrodes were applied and the recording of physiological parameters was tested, participants received ten training trials for each of three tasks to warm up and thereafter conducted the main tasks. The low WM block always preceded high WM blocks. The order of the high WM block and high WM block & FB was counterbalanced across participants.

Data reduction and statistical analyses

RTs to correct responses between 200 ms and 1500 ms only were analysed. Older people usually have a slower RT and higher level of sympathetic activity as well as a lower level of vagal activity in the baseline that may confuse Age Group by Condition interaction, i.e. the reactivity of these parameters to mental load. Therefore, age effects on reactivity could simply reflect age-related increases/decreases rather than condition-specific effects. To address this issue, the present study used log-transformed data to control for age-related differences in baseline performance. First, older adults often have larger variability in performance and cardiovascular data than younger adults. Thus, the assumption of homogeneous variances between groups is often violated. Second, the reactivity of each measure to cognitive load is calculated as differences between logarithms, which it equivalent to ratio scores. As a consequence, Age Group by Condition interactions are relatively independent of age differences in the baseline[26)]. The significant Age Group by Condition interaction effects on log-transformed data were discussed only. To explore the effects of WM load and Age Group on performance (RTs, lnRTs, omission percentage, false alarm percentage), an ANOVA was conducted with "Condition" (low WM load, high WM load, high WM load & FB) as a within-subject factor and Age Group (younger, older) as a between-subject factor. To test the effects of Condition and Age Group on cardiovascular variables (lnBRS, lnSBP, lnDBP, lnHR, lnLF-HRV, lnHF-HRV), an ANOVA was conducted with "Condition" (baseline, low WM load, high WM load, high WM load & FB, recovery) as a within-subject factor and Age Group (younger, older) as a between-subject factor. The Huynh-Feldt-corrected p-values were further reported, if necessary. The *t*-tests were applied to examine significant ANOVA effects. Statistical analyses were conducted by SPSS for Windows 17.0.

Table 2. Means, SD (in parenthesis) and *t*-tests for performance measures in older and younger workers

		Experimental conditions					*t*-tests
		1 Baseline	2 low WM load	3 high WM load	4 high WM load & FB	5 Recovery	
RT	Younger	–	353 (49)	485 (79)	454 (74)	–	not computed
	Older	–	357 (40)	525 (69)	502 (59)	–	not computed
lnRT	Younger	–	5.48 (0.13)	6.12 (0.16)	6.06 (0.16)	–	2 vs. 3***; 2 vs. 4***; 3 vs. 4 ***
	Older	–	5.86 (0.11)	6.21 (0.13)	6.17 (0.11)	–	2 vs. 3***; 2 vs. 4*** 3 vs. 4 ***
	t-tests		NS	***	***		
% FA	Younger	–	0.32 (0.60)	1.57 (1.54)	1.45 (1.15)	–	2 vs. 3***; 2 vs. 4***
	Older	–	0.34 (0.77)	2.64 (1.85)	2.72 (1.80)	–	2 vs. 3 ***; 2 vs. 4***
	t-tests		NS	***	***		
% OM	Younger	–	0.26 (1.06)	7.62 (7.68)	4.68 (4.33)	–	2 vs. 3 ***; 2 vs. 4***; 3 vs. 4***
	Older	–	0.22 (1.17)	10.68 (6.72)	6.23 (4.39)	–	2 vs. 3***; 2 vs. 4*** 3 vs. 4***
	t-tests		NS	*	NS		

RT − reaction time in ms (not statistically analysed); lnRT − log-transformed reaction time, % OM − omission percentage, % FA − false alarm percentage. *t*-tests: * − $p<0.05$; ** − $p<0.01$; *** − $p<0.001$, NS − non-significant.

Results

Means, SDs as well as significances of the *t*-tests for paired and independent comparisons are presented in the Table 2.

Behavioural data

The main effect of Condition was significant for all three performance measures, (Fs>82; ps <0.001), indicating lowered performance in both blocks with high WM load compared with the low WM load condition. As expected, older adults demonstrated longer RTs and made more false alarms than younger adults in both conditions with high WM load while no age differences under low WM load were found (Age Group * Condition, lnRT: F (2, 182) = 6.60, $p<0.004$, $\eta^2=0.07$; false alarms: F (2, 182) = 8.82, $p<0.001$, $\eta^2=0.09$). Despite the Age Group * Condition interaction on omission rate was marginally significant (F (2, 182) = 2.79, $p<0.07$, $\eta^2=0.03$) the *t*-tests showed a higher omission rate in older adults than in younger adults under high WM load only while in the low WM load block and the high WM load & FB block no age differences were observed, i.e. age differences in omission rate were abolished by FB application. Paired comparisons within groups revealed that both groups benefited from FB in terms of both RT and omission rate reduction (Fig. 1, Table 2); nevertheless, the age differences in RT and false alarms remained significant in the FB condition.

To examine FB effects on behavioural data regarding the effect size, a 2 × 2 ANOVA was additionally performed with Feedback (high WM load vs. high WM load & FB) as a within-subject factor and Age Group (younger, older) as a between subject factor. The FB effect sizes were: η^2 = 0.26 (lnRT) and $\eta^2=0.21$ (omission rate) while FB did not affect false alarm rate.

Cardiovascular data

The main effect of Condition was significant for all cardiovascular measures, (Fs>9; ps <0.001), indicating that n-back task was effective in inducing cardiovascular changes.

The main effect of Age Group was due to a higher SBP (F (1, 91) = 8.32, $p<0.005$, $\eta^2=0.08$), lower BRS (F (1, 91) = 78.29, $p<0.001$, $\eta^2=0.46$), lower LF-HRV (F (1, 91) = 37.42, $p<0.001$, $\eta^2=0.29$) and lower HF-HRV (F (1, 91) = 43.80, $p<0.001$, $\eta^2=0.33$) in older participants than in younger ones. No main effects of Age Group on DBP and HR were observed. The most interesting results were expressed in Age Group * Condition interactions due to age differences in the reactivity (WM load vs. baseline), recovery (recovery vs. baseline), and FB (high WM load & FB vs. high WM load only) effects.

The interaction effect of Age Group * Condition on SBP (F (4, 364) = 6.10, $p<0.001$, $\eta^2=0.06$) was due to a greater

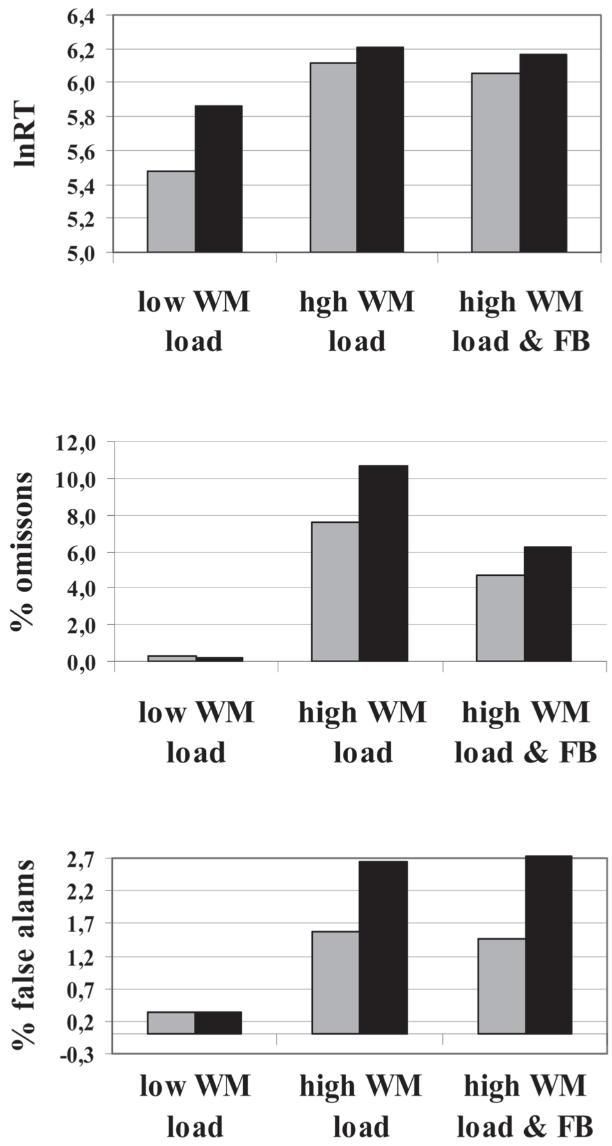

Fig. 1. Means of performance measures as a function of experimental conditions in younger (gray) and older (black) adults.
lnRT − log-transformed RTs;% omission − omission percentage,% false alarms − false alarms percentage.

SBP reactivity in older adults than in younger adults (Fig. 2A). The SBP in younger adults did not change under low WM, increased under both high WM load conditions and returned to baseline values in the recovery. By contrast, in the older group SBP already increased under low WM load, sharply rose under high WM load and did not recover from it. Paired comparisons showed age differences in SBP in all conditions except baseline. The FB did not affect SBP in both age groups.

The interaction effect of Age Group * Condition on DBP (F (4, 364) = 4.19, p<0.007, η^2=0.04) was also attributed to a greater DBP reactivity in older adults than in younger adults (Fig. 2B). The DBP first rose in both age groups at low WM loads with stronger effects in older adults. Under high WM load DBP continued to increase in older adults only while remained constant in younger adults. Paired comparisons showed age differences in DBP reactivity to both high WM load conditions only. Notably, the DBP did not recover in both age groups; however, the DBP difference in the recovery relative to the baseline was significantly larger in older adults than in younger adults. The FB did not affect DBP in both age groups.

The interaction effect of Age Group * Condition on BRS (F (4, 364) = 2.63, p<0.05, η^2=0.03) was due to age differences in reactivity patterns (Fig. 2C). In younger adults, BRS significantly increased under low WM load as compared to the baseline, then remained enhanced in both high WM load blocks and increased in the recovery above the baseline level. By contrast, the BRS in older adults first rose at lower WM loads, but thereafter decreased under high WM load and remained reduced in the recovery. Paired comparisons showed age differences in BRS in all conditions. The FB led to a BRS increase in younger adults but not in older adults (Table 3).

The interaction effect of Age Group * Condition on HR (F (4, 364) = 3.65, p<0.01, η^2=0.04) was attributed to three sources (Fig. 2D). First, in younger adults HR increased under low WM load against baseline while in older adults it did not. Second, the recovery effect (i.e. the difference between recovery and baseline) was larger in younger adults than in older adults. Third, HR decreased with FB in older participants but not in younger participants (Table 3).

The interaction Age Group * Condition on LF-HRV (F (4, 364) = 2.81, p<0.04, η^2=0.03) was due to a LF-HRV reduction with increasing WM load in older adults while LF-HRV did not vary with WM load in younger adults (Fig. 2E). Paired comparisons showed that LF-HRV differed between age groups in all conditions. The FB application increased LF-HRV in both age groups (Table 3).

The HF-HRV was not affected by the Age Group * Condition interaction (Fig. 2F). Paired comparisons revealed age differences in HF-HRV in all conditions. The FB increased HF-HRV in younger but not in older adults (Table 3).

To examine whether BRS may contribute to elevated SBP in older adults we computed Pearson correlations for each age group. At higher WM loads BRS negatively correlated with SBP in both groups while the correlation was stronger in older adults than in younger adults (Table 4).

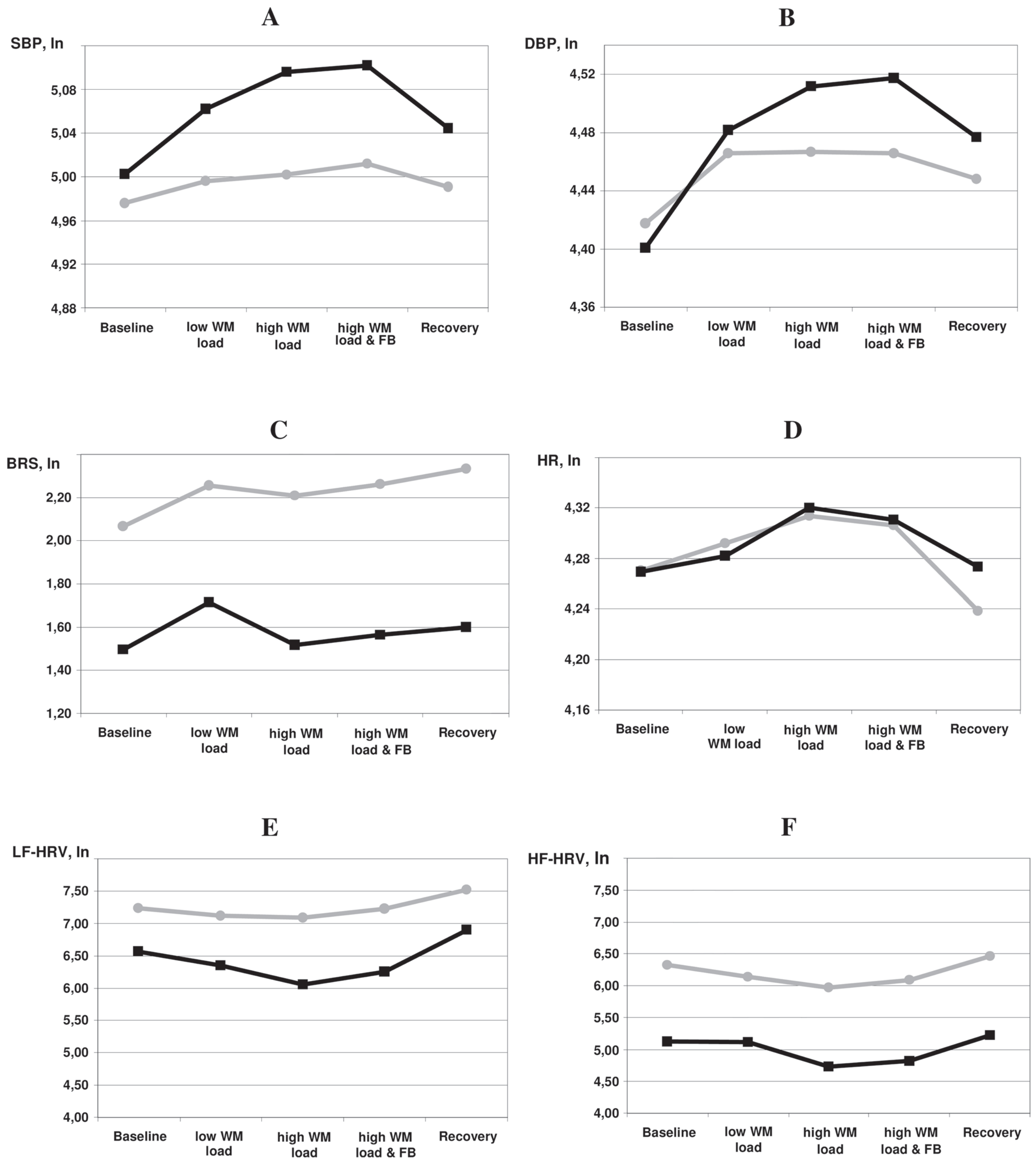

Fig. 2. Means of log-transformed cardiovascular measures as a function of experimental conditions in younger (gray) and older (black) adults.

A − systolic blood pressure, B − diastolic blood pressure, C − baroreflex sensitivity, D − heart rate, E − heart rate variability in LF band, F − heart rate variability in HF band.

To test FB effects on cardiovascular data concerning the effect size, a 2 × 2 ANOVA was performed with Feedback (high WM load vs. high WM load & FB) as a within-subject factor and Age Group (younger, older) as a between subject factor. The analysis confirmed significant FB effects mentioned above with following effect sizes: η^2=0.09 (BRS), η^2=0.17 (LF-HRV), η^2=0.07 (HF-HRV), η^2=0.31 (HR).

Table 3. Means, SD (in parenthesis) and *t*-tests for cardiovascular measures (log-transformed) in older and younger workers

		Experimental conditions					*t*-tests
		1 Baseline	2 low WM load	3 high WM load	4 high WM load & FB	5 Recovery	
lnSBP	Younger	4.98 (0.11)	5.00 (0.09)	5.00 (0.09)	5.01 (0.09)	4.99 (0.09)	1 vs. 3*; 1 vs. 4**; 4 vs. 5***
	Older	5.00 (0.15)	5.06 (0.14)	5.10 (0.13)	5.10 (0.12)	5.04 (0.13)	1 vs. 2***; 1 vs. 3***; 1 vs. 4***; 1 vs. 5***; 2 vs. 3**; 4 vs. 5**
	t-tests	NS	**	***	***	**	
lnDBP	Younger	4.42 (0.12)	4.47 (0.11)	4.47 (0.11)	4.47 (0.11)	4.45 (0.12)	1 vs. 2***; 1 vs. 3***; 1 vs. 4***; 1 vs. 5**; 4 vs. 5*
	Older	4.40 (0.18)	4.48 (0.15)	4.51 (0.13)	4.52 (0.12)	4.48 (0.15)	1 vs. 2***; 1 vs. 3***; 1 vs. 4***; 1 vs. 5***; 2 vs. 3**; 4 vs. 5**
	t-tests	NS	NS	*	*	NS	
lnBRS	Younger	2.07 (0.35)	2.25 (0.42)	2.21 (0.37)	2.26 (0.36)	2.33 (0.41)	1 vs. 2***; 1 vs. 3***; 1 vs. 4***; 1 vs. 5***; 3 vs. 4*
	Older	1.50 (0.45)	1.71 (0.38)	1.52 (0.45)	1.56 (0.46)	1.60 (0.47)	1 vs. 2***; 2 vs. 3***; 2 vs. 4***
	t-tests	***	***	***	***	***	
lnHR	Younger	4.27 (0.12)	4.29 (0.11)	4.31 (0.13)	4.31 (0.12)	4.24 (0.12)	1 vs. 2***; 1 vs. 3***; 1 vs. 4***; 1 vs. 5**; 4 vs. 5***
	Older	4.27 (0.13)	4.28 (0.12)	4.32 (0.13)	4.31 (0.12)	4.27 (0.13)	1 vs. 3***; 1 vs. 4***; 2 vs. 3***; 2 vs. 4***; 3 vs. 4*; 3 vs. 5***; 4 vs. 5***
	t-tests	NS	NS	NS	NS	NS	
lnLF-HRV	Younger	7.24 (0.69)	7.11 (0.60)	7.08 (0.68)	7.22 (0.72)	7.52 (0.83)	1 vs. 5*; 3 vs. 4***; 4 vs. 5***
	Older	6.56 (0.87)	6.35 (0.78)	6.06 (0.75)	6.25 (0.74)	6.90 (1.10)	1 vs. 2*; 1 vs. 3***; 1 vs. 4**; 2 vs. 3***; 3 vs. 4***; 4 vs. 5***
	t-tests	***	***	***	***	***	
lnHF-HRV	Younger	6.33 (0.86)	6.14 (0.87)	5.97 (0.97)	6.09 (0.95)	6.46 (1.04)	1 vs. 2*; 1 vs. 3***; 2 vs. 3**; 3 vs. 4*; 4 vs. 5***
	Older	5.12 (0.93)	5.11 (0.91)	4.72 (1.02)	4.82 (0.99)	5.22 (1.18)	1 vs. 3***; 1 vs. 4**; 2 vs. 3***; 4 vs. 5***
	t-tests	***	***	***	***	***	

SBP − systolic blood pressure, DBP − diastolic blood pressure, BRS − baroreflex sensitivity, HR − heart rate, LF-HRV − heart rate variability in LF band, HF-HRV − heart rate variability in LF band. *t*-tests: * − $p<0.05$; ** − $p<0.01$; *** − $p<0.001$, NS − non-significant.

Table 4. Pearson correlations between systolic blood pressure and baroreflex sensitivity as a function of age and working memory load

	Younger		Older	
	r	*p*	r	*p*
low WM load	−0.09	0.53	−0.30	0.04
high WM load	−0.27	0.05	−0.41	0.006
high WM load & Feedback	−0.34	0.02	−0.56	0.001

r − correlation coefficient, *p* − significance level.

In sum, older adults as compared to younger adults demonstrated higher DBP and SBP levels, lower HRV and BRS levels as well as greater SBP and DBP reactivity to WM load. The FB reduced omission rate and increased LF-HRV in both age groups. Moreover, the FB reduced HR in older adults while in younger adults facilitating FB effects on HF-HRV and BRS were obtained.

Discussion

Effects of working memory load

The fact that older participants responded more slowly and less accurately than their younger counterparts at higher WM loads (2-back task) but not at lower WM loads (0-back task) well replicates our previous data and widely agrees with other experiments demonstrated age-related performance decline in WM tasks[7, 11, 27]. Notably that the majority of studies was conducted in the population of healthy retirees. Duffner *et al.*[11] examined retirees (65–85 yr old) with the 2-back task similar to that used in our experiment. Our older participants responded faster (525 ms) than those in the cited study (597 ms) while accuracy (% hits minus % false alarms) was near the same (88% vs. 87%). Hence, WM impairments that have been usually found in retirees were already seen in our middle-aged participants, however, to a lesser extent.

We also found a greater SBP reactivity in older workers than in younger workers that fits well with other data (see reviews by[4, 5, 18]). Notably, SBP responses in older participants were disproportionally elevated already in the low WM load condition. The over-activation of task-specific brain areas in older adults at lower memory loads is a robust finding from memory research and has been interpreted as a compensatory resource mobilisation, see e.g.[3]. If we assume that the over-activation requires a heightened metabolic support, the SBP increase in our older participants may be seen as a compensatory mechanism providing strengthened perfusion these brain areas with blood. However, it remains unclear why older participants increased the SBP in an easy and well-practiced task. Psychological factors like test anxiety or negative aging stereotype may play an important role in memory performance and cardiovascular reactivity in older people[28, 29]. Levy *et al.*[29] found that those older participants who were exposed to negative aging stereotypes demonstrated heightened blood pressure responses to cognitive challenge compared with those exposed to positive aging stereotypes.

The decreased sensitivity of aortic and carotid baroreceptors in older people may be resulted in a reduced activity of parasympathetic neurons in the medulla that cannot quickly detect the subtle increases in blood pressure and compensate for them with an HR decrease via the baroreflex mechanism. Consequently, SBP may remain permanently enhanced under cognitive load[17]. Older adults in our experiment revealed the BRS reduction under high WM load that was accompanied by SPB and HR increases. By contrast, younger adults demonstrated an enhanced BRS throughout the experiment that paralleled a constant SBP. Moreover, the negative correlation between BRS and SBP was stronger in older adults than in younger adults. Hence, the elevated SBP reactivity in older adults may also be attributed to the rigidity of the cardiovascular function against task demands as indicated by a reduced BRS.

Age effects on cardiovascular reactivity to laboratory stressors are usually more pronounced for SBP than DBP while putative mechanisms of this phenomenon have not been discussed[5]. We can only speculate that this effect may partly be due to the DBP decline after age 50–60 yr, while SBP progression in the elderly has been reported[30]. In contrast to other aging studies, we found a higher reactivity to WM load in older adults than in younger adults for DBP. It is known that SBP is predominantly affected by cardiac contractility while DBP is more influenced by peripheral vascular resistance[31]. The DBP increase in both age groups at lower WM loads might be adaptive and probably due to resource mobilisation via increases in peripheral vascular resistance. However, at higher WM loads the DBP patterns differed between groups. Younger participants did not increase DBP while older participants continued to increase it. This indicates that older people use both cardiac contractility and peripheral vascular resistance mechanisms to meet task requirements. By contrast, younger adults could adapt to task demands by enhancements in peripheral resistance only and involved this mechanism already at lower WM loads. Taken together, WM load elicits a more global re-organisation of cardiovascular systems in older adults than in younger adults. Other reason for enhanced DBP reactivity to laboratory stressors in the elderly may be the predominance of passive coping strategies that are thought to increase peripheral resistance and thereby DBP[32].

Feedback effects

There is little evidence about FB effects on memory performance in older people. West *et al.*[9] demonstrated that a FB about the number of items remembered was sufficient to improve memory recall in older and younger adults. Moreover, FB led to a higher motivation and goal commitment with even stronger effects in older adults. Our data also revealed a clear-cut facilitating FB effect on omission rate when age differences were abolished in the FB condition. The facilitating FB effects in both age groups may be accounted for by reduction of perceived task difficulty because FB signalled correct responses in the majority of trials. This may have reduced the perceived task difficulty and tension and thereby cardiovascular costs. Nevertheless, FB did not influence age differences in reaction times and false alarms. The absence of FB effects on these parameters might be related to a number of reasons. It might be due to a higher distractibility in older adults relative to younger adults[33] while acoustic FB might have distracted older adults from the task and resulted in performance decline. However, the explanation appears to be unlikely as all participants extensively practiced the FB use during the training session. The attenuation of FB effects may also be partly attributed to task requirements as older adults have not enough time for an elaborated FB processing during the short response window of 1.5 s. Consequently, the FB utilisation might be different between age groups. Despite the short response window younger adults were able to process FB and cut the stimulus sequence into small subsequences. By contrast, the short response window may have elicited time pressure in older participants who may have used FB to increase their alertness level and on-task concentration. Age-related deficits in brain mechanisms underlying FB processing[10] may have also been responsible for persisted age differences in RTs and false alarms in the FB condition.

At the cardiac level the FB led to a reduction of cardiovascular costs in both age groups. However, the reduction had different origin in younger and older adults. The HR slowing in older adults walked along with LF-HRV increases while keeping high levels of DBP and SBP. As the LF-HRV reflects both sympathetic and vagal influences[13] the increases might have been interpreted as a reduction of sympathetic tone and increase of vagal tone. However, the absence of feedback-related HF-HRV changes and predominantly sympathetic control over HR in older adults[15] suggest that the HR reduction in the FB condition was predominantly due to reductions in sympathetic tone rather than to increases in vagal tone. By contrast, FB led to BRS and HF-HRV increases in younger adults reflecting vagal activation.

Notably, that FB effect sizes differed between dependent variables. The most prominent FB effects were obtained for HR, RT and omission rate (31%, 26%, 21% of explained variance respectively). The result appears to be of great practical relevance as a working memory training with FB may substantially improve WM performance and reduce HR in older workers who are exposed to higher WM loads.

Together, the results indicate that older workers and younger workers do not have the same FB benefits as indicated by persisted age differences in some performance parameters and cardiovascular costs in the FB condition. Nevertheless, FB helped older workers to partly compensate for WM deficits and reduce cardiovascular costs of WM load by moderate decreases in sympathetic tone. By contrast, in younger adults feedback-related performance improvements and reduction of cardiovascular costs were predominantly achieved by vagal activation.

Limitations of the study

The SBP reactivity has been considered as a predictor for cardiovascular risks[4, 34]. Despite the fact that WM demands in our study were associated with elevated SBP in older workers, it would be too straightforward to conclude that WM load inevitably leads to cardiovascular diseases. The duration of WM load appears to play an important role. Therefore, future research is needed to examine to what extent a long-term enhancement of cardiovascular costs are related to cardiovascular risks in the group of older workers who had to do complex work requiring WM. The better WM performance in our older workers than in the retirees from the Daffner's *et al.*[11] study suggests that the employment may mitigate the WM decline in older adults. However, we should be cautious with this interpretation as both samples were not matched for age and amount of pre-experimental practice in the n-back task.

Concluding remarks

The normal aging process is associated with complex changes in the autonomic control, such as heightened sympathetic tone, parasympathetic withdrawal, and blunted baroreflex sensitivity. Recent studies showed that cognitive load elicited activation of brain areas related to cardiovascular control and this activation was accompanied by suppression of the baroreflex[35]. Hence, older workers who usually respond to cognitive load with baroreflex suppression may have been at risk for hypertension. In turn, hypertensive elderly show a reduced cerebral blood flow in brain areas sub-serving working memory[36] and may compensate for it by inhibition of the baroreflex that leads to increases in blood pressure and so forth. Therefore, further research should address the relationship between brain mechanisms underlying cognitive processing and cardiovascular regulation. Performance FB appears to be a useful tool for working memory improvements in older workers and the effects of different FB types on performance should be analysed in more detail.

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