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Effects of Working Memory Load on Performance and Cardiovascular Activity in Younger and Older Workers

Sergei A. Schapkin · Gabriele Freude · Patrick D. Gajewski · Nele Wild-Wall · Michael Falkenstein

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Abstract
Background Working memory (WM) declines with ageing, and this may cause problems in older workers who have to do complex work requiring WM.
Purpose We tested the assumption that an increase in WM load negatively affects performance and results in impaired cardiovascular adaptation to changing task demands in older workers relative to younger ones.
Method Thirty-three younger (29±3 years) and 32 older (55±3 years) workers had to perform a visual 0-back (low WM load) and 2-back (high WM load) task. Heart rate (HR), heart rate variability (HRV), beat-to-beat blood pressure (BP) and baroreflex were registered.
Results In the high WM load condition, older adults responded more slowly and less accurately than younger adults, while no age effects in the low WM load condition were found. Older workers showed a higher systolic blood pressure (SBP) reactivity to high WM load as well as a diminished post-task recovery of SBP and HRV than younger workers. Factor analysis demonstrated a close relationship between HR, baroreflex and HRV and their modulation by a common factor ("vagal tone") in the younger group. By contrast, HR was more related to the "sympathetic" factor in the older group.
Conclusion The data suggest that older workers as compared with younger ones are impaired in tasks requiring WM, which is accompanied by enhanced cardiovascular "costs" in terms of increased SBP and reduced vagal control over HR.

Keywords Ageing · Working memory · Heart rate · Baroreflex · Blood pressure

S. A. Schapkin (✉) · G. Freude
Federal Institute for Occupational Safety and Health, Nöldnerstrasse 40-42, 10317 Berlin, Germany
e-mail: schapkin.sergei@baua.bund.de

P. D. Gajewski · N. Wild-Wall · M. Falkenstein
Leibniz Research Centre for Working Environment and Human Factors, Technical University of Dortmund, Ardeystr. 67, 44139 Dortmund, Germany

Introduction

Incremental ageing of the working population in Western Europe during the last two decades has resulted in the prolonged employment of older workers who have to do complex work requiring "executive" brain functions. The "executive" functions coordinate the lower-level cognitive processes like perception, attention and psychomotor coordination. Three main domains have been distinguished within executive functioning: mental set shifting, inhibition of irrelevant information and pre-potent responses as well as information monitoring and updating [1]. The latter domain represents working memory (WM) as a system with limited capacity where the action-related information is stored and continuously updated until the action is completed. Many studies demonstrated that older adults are disproportionately disadvantaged in tasks that rely heavily on WM [2–6]. Progressive loss of neurons in the structures underlying WM (e.g. dorsolateral prefrontal cortex and hippocampus) with advanced age may have been responsible for observed deficits [7, 8]. Older people can partly compensate for the deficits by an increase in effort, which is usually accompanied by the activation of prefrontal brain areas [9]. Recently, Wild-Wall et al. [10] reported enhanced amplitude of the contingent negative variation in frontal areas as an index for effortful motor preparation in older adults. In a memory task, older people show activations in brain areas that are usually not involved in the task performance in younger adults (e.g. medial frontal regions), while activity in regions that are usually involved in the task performance in younger adults is lower in older people [11].

The activation of additional brain areas under WM load may have consequences for the cardiovascular system of older people in terms of a heightened level of metabolic support to perfuse these brain areas with blood [12]. Indeed, maintenance of information in memory induces greater heart rate (HR) acceleration in older adults relative to younger ones [13]. In the last decade, the fluctuations in the inter-beat interval—the heart rate variability (HRV)—have been considered as a sensitive indicator for cardiovascular adaptation to task requirements [14]. HRV in the low frequency band (LF-HRV, 0.07–0.14 Hz) is related to short-term regulation of blood pressure (BP) and affected by both sympathetic and parasympathetic inputs, while the HRV in the high frequency band (HF-HRV, 0.15–0.40 Hz) is associated with parasympathetic (vagal) activity [15]. HRV progressively declines with cognitive and emotional load [14]. Hansen et al. [16] found superior WM performance in participants who showed an enhanced resting HF-HRV. The result suggests that efficiency of prefrontal brain function is related to efficient vagal control over the cardiovascular system. As vagal tone decreases with ageing [17, 18], older workers may have cardiovascular and performance deficits in tasks requiring executive control.

WM load usually affects the baroreflex mechanism, which regulates the maintenance of adequate blood perfusion of vital organs including the brain [19]. When systolic blood pressure (SBP) increases, the neurons in the medulla produce increases in parasympathetic tone resulting in the decrease of HR and heart contractility. The SBP reduction leads to decreases in parasympathetic tone and increases in sympathetic tone, producing the increase in HR and heart contractility. The baroreflex sensitivity (BRS) shows the magnitude of change in heart period (e.g. HR^{-1}) relative to change in SBP. The greater the baroreflex sensitivity, the quicker and more effective the cardiovascular system can adapt to changing task demands. As the baroreflex becomes reduced with advanced age [20], it may contribute to less efficient adaptation to WM load in older workers.

Data on age differences in speed and magnitude of hemodynamic responses to mental load (i.e. cardiovascular reactivity) are equivocal. Some studies reported the increase in reactivity with age [21, 22], while an age-related reduction in the reactivity was found in other studies [23–26]. Jennings et al. [21] found a reactivity increase in men aged from 46 to 64 years; however, no data for younger groups were presented for comparison. The reduced reactivity in older adults in the study by Butcher and Stocker [24] might be partly due to the relatively small sample size and short tasks that might lower the power of that study to detect age differences. Some studies found lowered HR reactivity in older people when an intense emotional load was applied [25, 26]. However, it may be attributed to a better ability of older people to regulate their emotions [27]. Moreover, single measures like HR cannot provide sufficient information to highlight mechanisms of cardiovascular reactivity. Finally, some studies did not find age effects on cardiovascular reactivity at all [28]. Together, the findings suggest that differences in methodology and sample characteristics must be taken into account when age effects on the reactivity were discussed.

Most researchers agree that rapid turn-off of physiological parameters after stressor is an index of an efficient adaptation to stress [14, 30–32]. As the post-task recovery is usually delayed with ageing [23, 32], the diminished recovery may be associated with performance decline and cardiovascular pathogenesis in older workers.

The Present Study

The *n*-back task is a widely accepted method to examine WM processes. In the classical version of the task, participants are presented with a sequence of stimuli and are required to press a key if the stimulus is identical to the stimulus *N* positions back in the sequence. The increase of the *N* (i.e. the number of stimuli kept in memory) increases WM load. A considerable amount of research using *n*-back task has demonstrated a performance decline in older adults relative to younger ones [2, 4, 6]. In our version of the *n*-back task, participants had to memorise a sequence of successively presented Latin letters and to respond when the letter was identical to the letter two trials previously, i.e. 2-back task (high WM load condition). In the 0-back condition, they had to respond to the letter "X" as quickly as possible. Although the 0-back task does not require WM operations, it was labelled "low WM load condition" for easier reading.

The above studies suggest an increase in sympathetic activity and a decrease in parasympathetic activity with ageing. To examine this, we first aimed to elucidate how different measures are related to both branches of autonomic cardiac control. In statistical terms, we assumed two relatively independent "factors"—the "sympathetic tone" and the "vagal tone" underlying different cardiovascular measures. BP is thought to be predominantly affected by a more indirect and slower sympathetic pathway, while HR and HRV are mainly controlled by a parasympathetic system which acts more rapidly and frequently [33]. Hence, the mechanism providing a quick compensatory HR deceleration if BP increases (i.e. baroreflex) may also be predominantly associated with vagal tone. Consequently, baroreflex was expected to be more related to HR and HRV than to SBP and DBP. We also hypothesized that a reduction of the vagal tone with ageing would cause a lowered correlation between HR, HRV and baroreflex and lowered factor loadings of the variables for the vagal factor in the older group. By contrast, a close interrelation of the variables within the vagal factor in younger people due to more efficient parasympathetic control was hypothesized.

Even though age effects on BP, HR and HRV reactivity and recovery have been examined in numerous studies, the baroreflex changes have not been documented sufficiently. In the present study, baroreflex was reliably measured on a beat-by-beat basis providing a clearer picture of age differences in cardiovascular regulation than in the experiments using discrete baroreflex measurements. We assumed a lowered baroreflex in older people that cannot provide a quick compensatory HR decrease and would result in permanently increased SBP under WM load as well as in the recovery period. As the HF-HRV is predominantly (if not exclusively) a manifestation of vagal control of the heart [33], we assumed a reduced resting HF-HRV and its diminished post-task recovery in older workers relative to younger ones. Given an age-related increase in sympathetic control and a decrease in vagal control with ageing, older participants would demonstrate a higher sympathetic reactivity and lower vagal reactivity to WM load than younger participants.

Method

Participants

Thirty-three healthy younger workers and 32 healthy older workers were recruited through advertisements in local newspapers. 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. The percentage of college/university graduates as well as the percentage of office workers was higher in the older group than in the younger one, while the percentage of non-office workers was higher in the younger group than in the older one. Older participants also had a higher body mass index (BMI) than younger participants. Health complaints were checked in a pre-selection phone interview by a WAI questionnaire [34]. The exclusion criteria were cardiovascular, neurological or psychiatric disorders, head injury, use of psychoactive medications or drugs. Participants who have a daily consumption of more than 20 cigarettes, more than 1 L of coffee, more than 500 ml of beer or 200 ml of dry wine were also excluded. Education level, main work activities as well as their duration within a working day were assessed by a questionnaire. Only participants who met the above criteria, had at least 6 months of work experience and were currently employed with at least 20 h per week were invited to a pre-selection session (see "Procedure" section). 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.

Task

Twenty-five 12×18-mm different Latin letters were presented successively in white on 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 press a key if a letter was identical to the letter presented two trials previously. The low WM load block consisted of 189 trials, while the high WM load block consisted of 388 trials. The target probability (20%), physical and temporal features of both tasks were identical to avoid confusion with the WM load effect.

Cardiovascular Measures

Electrocardiogram (ECG) was taken throughout the session with the "Suempathy-100" system (Suess Medizintechnik LTD, Germany). Beat-to-beat BP was registered continuously from the left middle finger using a Finapres device (Ohmeda, USA).[1] Cardiovascular variables were measured in task blocks as well as during 90 s baseline and 90 s recovery. 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. The shifting window procedure revealed 13 data points in the baseline and recovery, which are needed to assess reliable cardiovascular values. ECG artefacts were corrected offline. HRV and baroreflex were computed offline by the trigonometric regressive spectral analysis [35] based on the Cosinor method. The advantage of such an analysis is that data can be assessed in non-equidistant steps (in contrast to Fourier transformation), and it also minimises problems due to insufficient frequency resolution and aliasing, and can assess data segments of various length. The analysis

[1] The Finapres device reveals generally enhanced BP values relative to those obtained via brachial cuff due to differences in measurement technique.

Table 1 Demographic and cognitive characteristics of the participants

	Younger		Older		*t* test	
	Mean	StD	Mean	StD	*t*	*p*
n	33		32			
Age, years	29.06	3.45	54.53	3.10		
Age range, years	21–35		51–63			
% Women	55		53			
% College or university graduates	36		72			
% Office workers	39		70			
% Non-office workers (workman, policeman, nurse, sport coach etc.)	51		15			
% Executives	10		15			
% Smokers	31		36			
Cigarettes per day	4.30	5.83	4.73	8.09	−0.20	0.84
Body mass index	22.98	3.32	24.96	3.83	−2.15	0.04
Simple reaction (visual), ms	240.31	21.62	238.97	49.49	0.14	0.89
Simple reaction (acoustic), ms	204.47	41.88	212.29	49.91	−0.68	0.50
Landolt C (time, s)	126.79	36.92	134.07	38.66	−0.77	0.45
Landolt C (error number)	1.25	2.84	1.19	1.22	0.10	0.92
Tapping (accuracy)	8.11	1.59	7.26	3.11	1.37	0.18
Stroop interference (time for the incongruent condition, s)	23.19	4.06	26.41	7.45	−2.14	0.04
Sensomotoric coordination (time, s)	47.67	15.60	55.46	25.02	−1.49	0.14
Sensomotoric coordination (error number)	24.72	14.27	26.97	15.58	−0.60	0.55
Labyrinth test (time, s)	132.28	49.31	154.87	63.90	−1.57	0.12
Clock monitoring test (deviation from the target, degree)	46.59	14.74	56.10	24.40	−1.88	0.07

detects underlying rhythms using the following equation: $F = \sum(\text{variable}(t_i) - \text{Reg}(t_i))^2 \Rightarrow \text{Minimum}$. In this function, non-equidistant data (i.e. RR interval and BP) are used, and parameters of amplitude (a), phase shift (φ) and frequency (ω) are represented as a trigonometric function in which $\text{Reg}(t_i) = a \times \sin(\omega t_i + \varphi i)$. Using regression analysis, amplitude, frequency and phase shift can be estimated using partial differential quotients (i.e. $\delta F/\delta a$, $\delta F/\delta\omega$ and $\delta F/\delta\varphi$). The HRV parameters were computed according to guidelines for perioperative cardiovascular evaluation for noncardiac surgery [15] in the low frequency domain (0.04–0.14 Hz) and high frequency domain (0.15–0.4 Hz).

Procedure

The pre-selection session was conducted between 9 a.m. and 12 noon before the main experiment. Arterial BP was measured via brachial cuff before, in the middle and at the end of the session to exclude hypotensive or hypertensive persons. To assess the mental status of participants, short versions of classical cognitive tests with the computer system "Age+Fitness" were conducted (Poethig Ltd., Germany). In the simple reaction time tests to visual and acoustic stimuli, participants had to press a key as quickly as possible when they saw a red cross on the computer screen or heard a tone. Focused attention was measured with the "Landolt test" where a list of 600 broken rings was presented, and the rings broken at the top (targets) had to be identified as quickly and as accurately as possible. Speed of voluntary movement was assessed with the "tapping test" when participants were required to tap with an electronic pen as quickly as possible and try to keep the constant tapping frequency for 1 min. The Stroop colour word test comprised three blocks of trials: (1) 30 colour squares, (2) 30 words denoting colours and written in black, and (3) 30 words denoting colours and written in incongruent colours. In each block, participants had to respond verbally to which colour (first block), word (second block) and colour (third block) they saw. The third block was considered to measure the executive control involved to resolve the word–colour interference. To test sensomotoric coordination, participants had to follow the middle of a snake-like curve with an electronic pen and avoid touching curve borders. Implicit learning ability was examined with the "Labyrinth test" which comprised 14×14 cells in which participants had to "go" with an electronic pen from the left lower cell to the right upper cell while an acoustic feedback signalled the correctness of the "steps". In the "clock monitoring test", participants were required to stop the watch hand at the

12th position after three full rotations. The test results are presented in Table 1. Older adults only performed worse than younger adults in the Stroop test, which relies on executive control, while there were no age differences in the other cognitive tests. At the end of the pre-selection session, participants received some training blocks in the 0-back task and the 2-back task until they attained 90% correct responses.

The main experiment was conducted within 1 week after the pre-selection session. The experiment started between 9 a.m. and 10 a.m. and finished approximately between 12 noon and 1 p.m., while a 10-min break was given in the middle of the experiment. Participants filled in questionnaires on detailed job characteristics, personality traits, health status, sleep quality and consumption of psychoactive substances (caffeine, nicotine, alcohol and drugs). Participants were requested to refrain from consuming coffee, tea and 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 the 0-back task and the 2-back task to warm up for the main experiment. Thereafter, participants conducted the 0-back task and the 2-back task lasting about 6 and 12 min, respectively. To examine the cardiovascular adaptation to increasing WM load, we did not randomise conditions of low and high WM load, i.e. the low WM block always preceded the high WM block. This design appears to be appropriate to examine changes in physiological responses to WM load, which increases stepwise [36, 37]. Moreover, according to the above studies, we expected that older adults compared with younger ones need more time to recover from the high WM block. If the high WM block was presented first, it would have a detrimental after-effect on cardiovascular measurements and/or performance in the following low WM block, and the effect would be greater in older adults than in younger ones.

Data Analysis

Older people usually have a slower reaction time and higher level of sympathetic activity, as well as a lower level of vagal activity in the baseline that may confuse age group × 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, we used log-transformed measures to control age-related differences in baseline performance. Older adults often show larger variability in performance than younger adults. Thus, the assumption of homogeneous variances between groups is often violated. This can largely be avoided if analyses are based on log-transformed measures that are equivalent to ratio scores and thereby less sensitive to differences in baseline scores [37]. Responses faster than 200 ms were excluded from the analysis. To explore the effects of WM load and age group on performance (log-transformed reaction time, omission percentage and false alarm percentage), a repeated ANOVA was conducted with "condition" (low WM load and high WM load) as a within-subject factor and age group (younger and older) as a between-subject factor. To test the effects of condition and age group on cardiovascular variables (lnBRS, lnSBP, lnDBP, lnHR, lnLF-HRV and lnHF-HRV), a repeated ANOVA was conducted with "condition" (baseline, low WM load, high WM load and recovery) as a within-subject factor and age group (younger and 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. To explore age differences in the relationship between cardiovascular variables, a principal component factor analysis was performed for the older and the younger groups separately. Statistical analyses were conducted by SPSS for Windows 14.0.

Results

Behavioural Data

Means, SDs as well as significances of the t tests for paired and independent comparisons are presented in Table 2. The main effect of age group was significant (percent omission: $F(1, 63)=7.02$, $p<.01$, $\eta^2=0.10$; percent false alarm: $F(1, 63)=10.99$, $p<.002$, $\eta^2=0.15$), indicating that older adults responded less accurately than younger adults. The interactions of age group × condition showed slower (reaction time (ln): $F(1, 63)=3.91$, $p<.05$, $\eta^2=0.06$) and less accurate responses (percent omission: $F(1, 63)=4.48$, $p<.008$, $\eta^2=0.11$; percent false alarm: $F(1, 63)=9.18$, $p<.004$, $\eta^2=0.13$) in older adults relative to younger ones under high WM load only (Table 2 and Fig. 1), while no age differences in performance under low WM load was found.

Factor Analysis of the Cardiovascular Data

Scree plots confirmed a similar two-factor solution for both age groups (Fig. 4). As expected, one factor comprised baroreflex, LF-HRV and HF-HRV ("vagal tone"), while another was represented by SBP and DBP measures ("sympathetic tone"). However, factor structures differed between younger and older adults concerning HR. In younger adults, baroreflex and HF-HRV negatively correlated with HR and relied on the vagal factor. By contrast, in older adults, HR was decoupled from the vagal factor and loaded the sympathetic factor in which HR correlated positively with SBP and DBP (Table 3).

Table 2 Means and standard deviations (in brackets) for younger and older adults

	Experimental conditions				*t* tests
	Baseline 1	Low WM load 2	High WM load 3	Recovery 4	
ln reaction time					
Younger, mean (SD)	–	5.86 (0.13)	6.14 (0.18)	–	2 vs. 3***
Older, mean (SD)	–	5.86 (0.10)	6.22 (0.14)	–	2 vs. 3***
t tests		ns	*		
%FA					
Younger, mean (SD)	–	0.26 (0.41)	1.55 (1.08)	–	2 vs. 3**
Older, mean (SD)	–	0.44 (0.90)	2.66 (1.35)	–	2 vs. 3**
t tests		ns	***		
%OM					
Younger, mean (SD)	–	0.23 (0.96)	7.02 (6.47)	–	2 vs. 3***
Older, mean (SD)	–	0.23 (1.33)	11.41 (6.45)	–	2 vs. 3***
t tests		ns	**		
lnHR					
Younger, mean (SD)	4.23 (0.15)	4.26 (0.14)	4.28 (0.16)	4.19 (0.14)	1 vs. 2*
					2 vs. 3*
					3 vs. 4***
					1 vs. 4***
Older, mean (SD)	4.28 (0.13)	4.28 (0.12)	4.32 (0.13)	4.27 (0.14)	2 vs. 3***
					3 vs. 4***
t tests	ns	ns	ns	**	
lnSBP					
Younger, mean (SD)	4.97 (0.13)	4.99 (0.11)	5.01 (0.11)	4.98 (0.12)	
Older, mean (SD)	5.00 (0.16)	5.05 (0.15)	5.09 (0.13)	5.05 (0.12)	1 vs. 2**
					2 vs. 3**
					3 vs. 4**
					1 vs. 4*
t tests	ns	ns	**	*	
lnBRS					
Younger, mean (SD)	2.14 (0.45)	2.40 (0.48)	2.34 (0.43)	2.48 (0.44)	1 vs. 2***
					3 vs. 4**
					1 vs. 4***
Older, mean (SD)	1.41 (0.46)	1.64 (0.39)	1.44 (0.45)	1.46 (0.49)	1 vs. 2**
					2 vs. 3**
t tests	***	***	***	***	
lnHF-HRV					
Younger, mean (SD)	6.54 (1.25)	6.37 (1.17)	6.25 (1.14)	6.89 (1.14)	1 vs. 2*
					3 vs. 4***
					1 vs. 4**
Older, mean (SD)	4.94 (1.17)	4.90 (1.16)	4.45 (1.13)	4.91 (1.15)	2 vs. 3***
					3 vs. 4***
t tests	***	***	***	***	

Table 2 (continued)

	Experimental conditions				*t* tests
	Baseline 1	Low WM load 2	High WM load 3	Recovery 4	
lnDBP					
Younger, mean (SD)	4.38 (0.13)	4.45 (0.12)	4.45 (0.13)	4.44 (0.14)	ns
Older, mean (SD)	4.39 (0.17)	4.46 (0.15)	4.49 (0.12)	4.47 (0.14)	ns
t tests	ns	ns	ns	ns	
lnLF-HRV					
Younger, mean (SD)	7.22 (0.96)	7.15 (0.74)	7.13 (0.81)	7.51 (0.96)	ns
Older, mean (SD)	6.45 (0.89)	6.14 (0.83)	5.87 (0.84)	6.65 (1.18)	ns
t tests	***	***	***	**	

Cardiovascular measures (log-transformed): *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 HF band. Behavioural measures: *ln reaction time* log-transformed reaction time, *%OM* omission percentage, *%FA* false alarm percentage

*$p<.05$; **$p<.01$; ***$p<.001$ (*t* tests); *ns* non-significant

Cardiovascular Reactivity and Recovery

A main effect of age group indicated higher SBP ($F(1, 63)=4.08$, $p<.05$, $\eta^2=0.06$), lower baroreflex ($F(1, 63)=79.21$, $p<.001$, $\eta^2=0.56$), lower LF-HRV ($F(1, 63)=25.91$, $p<.001$, $\eta^2=0.29$) and lower HF-HRV ($F(1, 63)=39.56$, $p<.001$, $\eta^2=0.39$) in older participants than in younger ones. The DBP and HR did not vary with age. The most interesting results were expressed in age group×condition interactions due to age differences in the reactivity pattern and the recovery magnitude (Table 2 and Figs. 2 and 3).

The interaction effect of age group×condition on baroreflex ($F(3, 189)=4.19$, $p<.01$, $\eta^2=0.06$) was due to two sources. In younger adults, baroreflex significantly increased under low WM load as compared to the baseline, then did not change under high WM load and remained increased in the recovery above the baseline level (Fig. 2a and Table 2). The baroreflex in older adults first increased under low WM load as in the younger group but thereafter decreased under high WM load and remained reduced in the recovery.

The interaction effect of age group×condition on HR ($F(3, 189)=6.04$, $p<.001$, $\eta^2=0.09$) was also attributed to reactivity differences between older and younger adults. In younger adults, the HR increase with increasing WM load as well as the HR decrease in the recovery below baseline scores was revealed (Fig. 2b and Table 2). By contrast, in the older group, HR under low WM load did not differ from the baseline but significantly increased under high WM load and returned to baseline scores in the recovery.

The interaction effect of age group×condition on HF-HRV ($F(3, 189)=3.87$, $p<.02$, $\eta^2=0.06$) was due to the fact that younger adults responded to low WM load with the reduction of the HF-HRV that did not change further under high WM load and increased sharply over baseline scores in the recovery (Fig. 2c and Table 2). By contrast, in the older group, HF-HRV did not increase under low WM load, then decreased under high WM load and returned to the baseline in the recovery.

Even though the "age group×condition" interaction effect on SBP was marginally significant ($F(3, 189)=2.36$, $p<.06$, $\eta^2=0.04$), the paired *t* tests showed that SBP progressively rose with increasing WM load in older adults but not in younger adults. Importantly, age differences in SBP were absent in the baseline and under low WM load while they were only found under high WM load and in the recovery (Table 2).

To examine age differences in the recovery magnitude, we compared the recovery and baseline scores (i.e. recovery minus baseline [38]) for each age group. A larger recovery (Fig. 3) effect was found in younger adults relative to older ones on baroreflex, HR and HF-HRV. It resulted in higher scores in the recovery than in the baseline for younger adults, while no differences between the baseline and the recovery in older adults were found. Notably, SBP did not differ between the baseline and the recovery in younger adults, i.e. it returned to the baseline after WM load. By contrast, SBP was significantly higher in the recovery relative to the baseline in older adults, i.e. they did not demonstrate the SBP recovery at all.

There were no age differences in reactivity of DBP and LF-HRV to experimental conditions.

In summary, in younger adults, HR was related to the vagal factor, while in older adults, it was related to the sympathetic factor. The older group relative to the younger one demonstrated a higher level of sympathetic reactivity as well as a lower level of parasympathetic reactivity to WM load and diminished parasympathetic recovery. The cardiovascular reactivity pattern differed between the age groups.

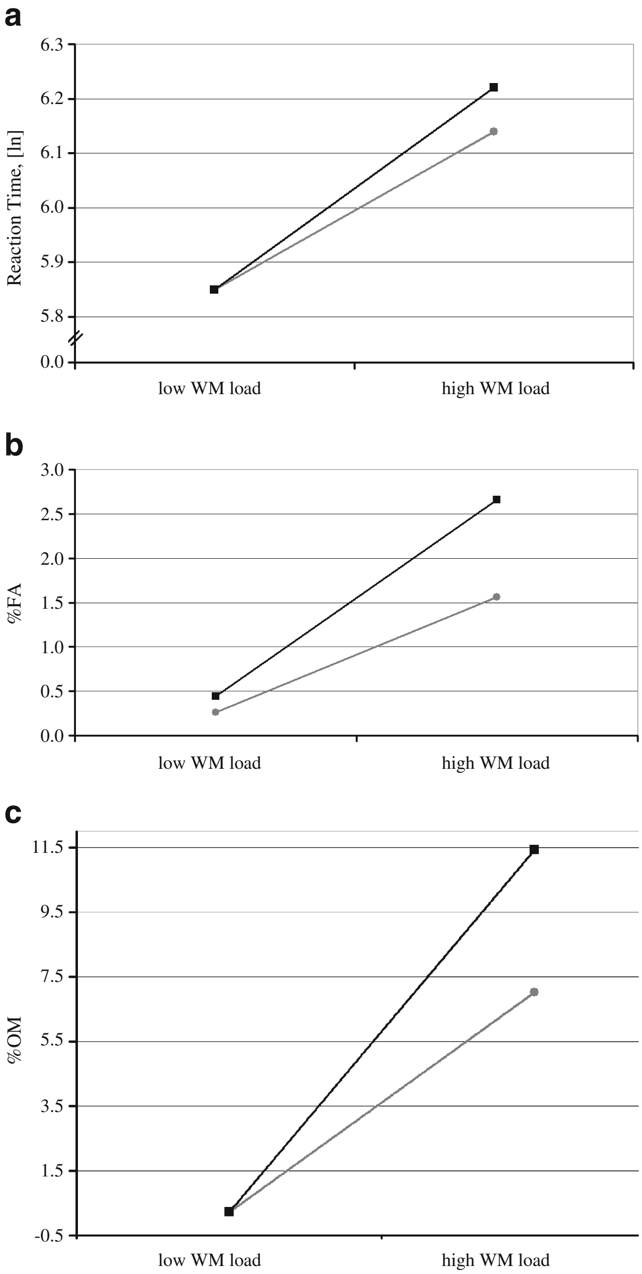

Fig. 1 Means of reaction time, omission rate and false alarm rates as a function of experimental conditions in younger (*gray*) and older (*black*) adults

Discussion

Performance

We first aimed at replicating the previous data on age-related performance decline in WM load. As expected, WM load resulted in slower and less accurate responses in older participants relative to younger ones. The result is in agreement with studies which reported that older adults are disproportionately disadvantaged in WM tasks [2–6, 39]. Notably, error percentage in the 2-back task was generally low (about 8%) suggesting moderate task demands. However, the age-related performance decline was evident even in the task of intermediate difficulty and after a considerable amount of training trials. The analysis of error type under high WM load yielded many more omissions in older adults than in younger adults (Fig. 2b, c). The effect may be accounted for by the adoption of an accuracy-oriented strategy, which results in an increase in accuracy at the cost of processing speed [40]. As a short response window (1.5 s) was applied in our study, such a strategy may have been of disadvantage for older adults who could correctly recognize targets but did not have enough time for response preparation. This interpretation is supported by the data of Missionnier et al. [39], who used a similar 2-back letter task but a longer response window (5 s). Despite the fact that the participants in the study of Missionnier et al. [39] were roughly 20 years older (i.e. about 75 years old) than those who participated in our study (i.e. about 55 years old), they made about 6% fewer errors than our older participants. The comparison of the two studies suggests that lengthening the response window can facilitate rehearsal processes and thereby improve WM performance in older people.

Relationship Between Cardiovascular Variables

Based on the literature [14, 33], we assumed that HR deceleration as well as the increase in baroreflex and HRV are related to a common factor (i.e. vagal tone), while BP measures are associated with another factor (sympathetic tone). Indeed, the factor analysis of cardiovascular variables revealed a similar two-factor solution for younger and older adults representing the vagal (baroreflex and HRV) tone and the sympathetic (SBP and DBP) tone, respectively (Table 3 and Fig. 4). However, the relationship of HR to other variables differed between age groups. In younger adults, baroreflex and HRV correlated negatively with HR within the vagal factor, i.e. the increase in baroreflex sensitivity led to a compensatory deceleration of HR. By contrast, HR in the older group was decoupled from the “vagal” factor and was positively related to the sympathetic factor. Moreover, HR positively correlated with SBP within the sympathetic factor, suggesting impairments in baroreflex that cannot provide effective HR regulation in older adults. Hence, factor analysis suggests reduced vagal and enhanced sympathetic control over HR in older participants, indicating lowered adaptation of their cardiovascular systems to cognitive load.

An important question of the present study was whether older workers can compensate for WM decline and which cardiovascular “costs” may emerge during the adaptation to cognitive load. The concept of “allostasis” [31] considers

Table 3 Factor loadings of cardiovascular data for younger and older adults

Variables/factor	Younger		Older	
	"Vagal"	"Sympathetic"	"Vagal"	"Sympathetic"
lnSBP–baseline		0.76		0.79
lnSBP–low WM load		0.88		0.83
lnSBP–high WM load		0.86		0.76
lnSBP–recovery		0.86		0.83
lnDBP–baseline		0.89		0.64
lnDBP–low WM load		0.88		0.79
lnDBP–high WM load		0.87		0.78
lnDBP–recovery		0.79		0.70
lnBRS–baseline	0.81		0.49	
lnBRS–low WM load	0.90		0.83	
lnBRS–high WM load	0.88		0.83	
lnBRS–recovery	0.77		0.61	
lnLF-HRV–baseline	0.70		0.55	
lnLF-HRV–low WM load	0.77		0.75	
lnLF-HRV–high WM load	0.80		0.88	
lnLF-HRV–recovery	0.66		0.73	
lnHF-HRV–baseline	0.90		0.79	
lnHF-HRV–low WM load	0.94		0.85	
lnHF-HRV–high WM load	0.92		0.91	
lnHF-HRV–recovery	0.86		0.77	
lnHR–baseline	−0.65			0.54
lnHR–low WM load	−0.75			0.51
lnHR–high WM load	−0.71			0.49
lnHR–recovery	−0.68			0.47

Factor loadings less than 0.40 are omitted. Extraction method: principal component. Two-factor solution was rotated via Oblimin with Kaiser normalization, delta=0

coping with a challenging situation and rapid recovery from it as an adaptive regulatory process that provides long-term stability of physiological functioning. We assumed that the adaptation has distinct facets like (1) maintenance of the stable level of cardiovascular activity at rest, (2) the task-related reactivity and (3) the post-task recovery. These aspects have been widely discussed in literature [20, 21, 23, 33, 38, 41]. However, only one of them has been the subject of common ageing studies. In the present study, we examined the three aspects of adaptation within an experimental design when older and younger workers faced a WM load.

Resting Level of Cardiovascular Activity

Based on the data on age-related activation of additional brain areas in WM tasks [12, 14, 15], we assumed a heightened level of sympathetic activity as well as a lower level of parasympathetic activity in older adults relative to younger ones. As predicted, older adults showed a decreased baroreflex and HF-HRV. The results largely coincide with other data on reductions in the resting vagal tone with advanced age [17, 18]. The vagal withdrawal may contribute to an enhanced SBP in older participants through lowered baroreflex. Indeed, in the present study, lowered baroreflex is accompanied by enhanced SBP, suggesting the reduced "alertness" of cardiovascular systems and hence reduced adaptation to cognitive demands in older adults. Notably, the heightened resting SBP may not only have short-term effects on task performance but may also be indicative of long-term cardiovascular risks in older people. For example, Steptoe et al. [20] reported that enhanced SBP is associated with elevated fasting low-density lipoprotein cholesterol levels and with lower concentrations of high-density lipoprotein cholesterol levels, which are prospectively related to an increased risk of coronary heart disease. The longitudinal study by Kilander et al. [41] demonstrated "protective" long-term effects of diminished DBP at rest. They showed that low DBP among 50-year-old men predicted reduced cardiovascular risks and superior cognitive performance 20 years later, irrespective of education and occupation. In summary, the results of resting cardiovascular activity are consistent with data on the increase in resting sympathetic activity and the decrease in parasympathetic activity with advanced age [33].

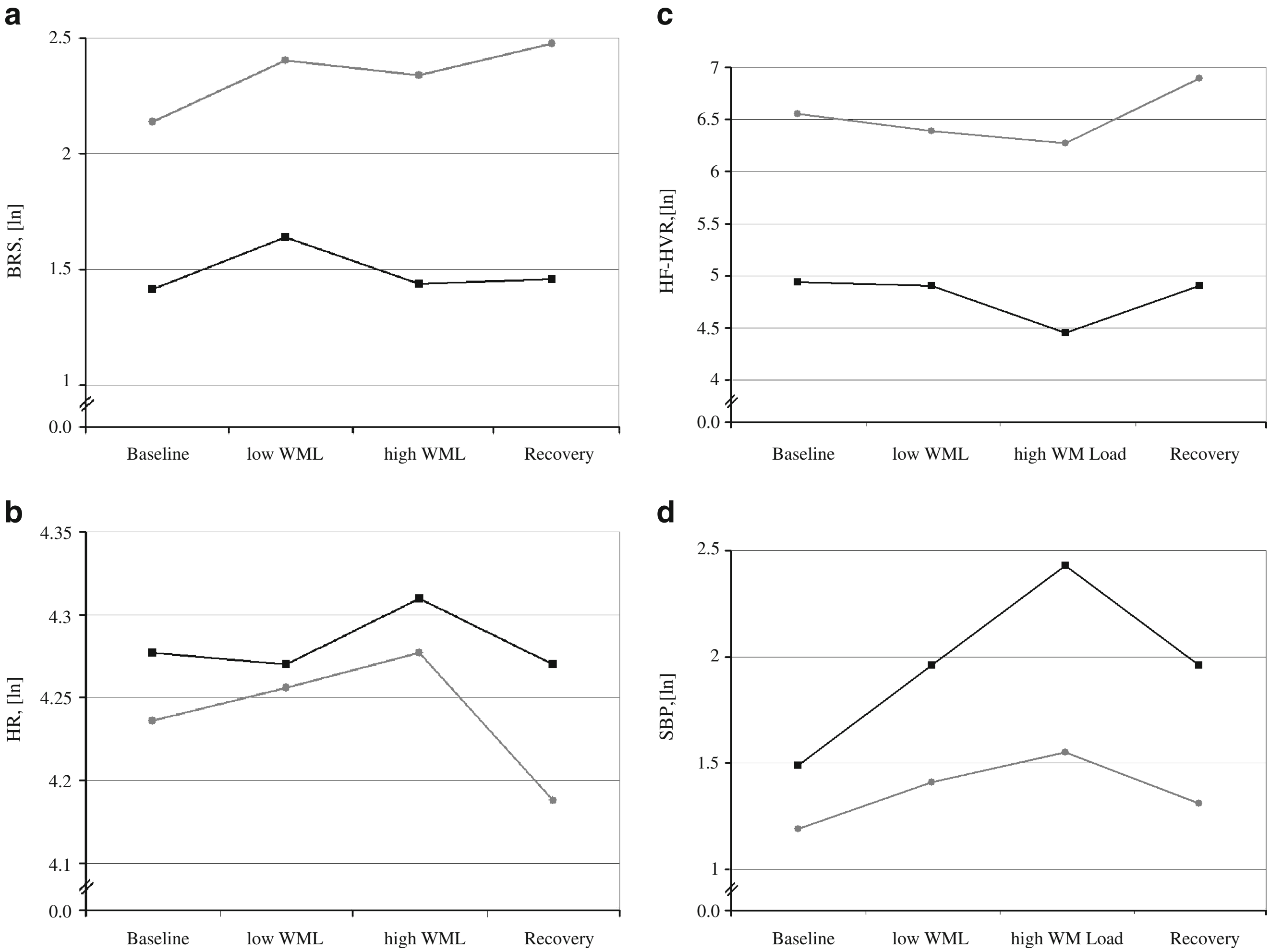

Fig. 2 Means of cardiovascular measures as a function of experimental conditions in younger (*gray*) and older (*black*) adults (log-transformed). **a** Baroreflex sensitivity (BRS, millimetres of mercury per millisecond). **b** Heart rate (HR, beat per minute). **c** Heart rate variability in HF band (HF-HRV, per square milliseconds). **d** Systolic blood pressure (SBP, millimetres of mercury)

Cardiovascular Reactivity

As predicted, we found an age-related increase in SBP reactivity and a decrease in reactivity of variables which are associated with vagal tone (baroreflex and HF-HRV). Our data are in line with other studies which reported the heightened BP reactivity [21, 22]. The increased SBP reactivity in older adults might be due to stiffness of the

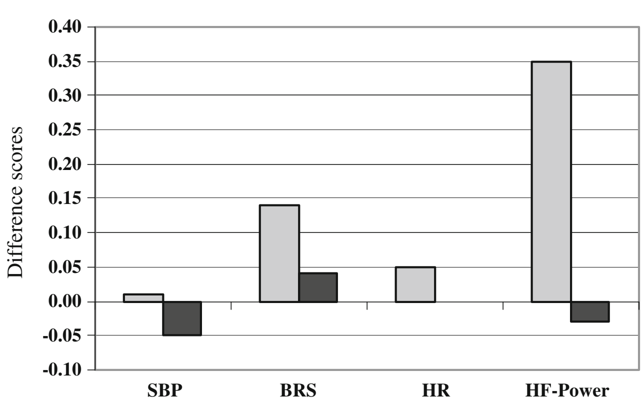

Fig. 3 Recovery effects on cardiovascular data (recovery minus baseline) in younger (*gray*) and older (*black*) adults. For abbreviations, see Fig. 2

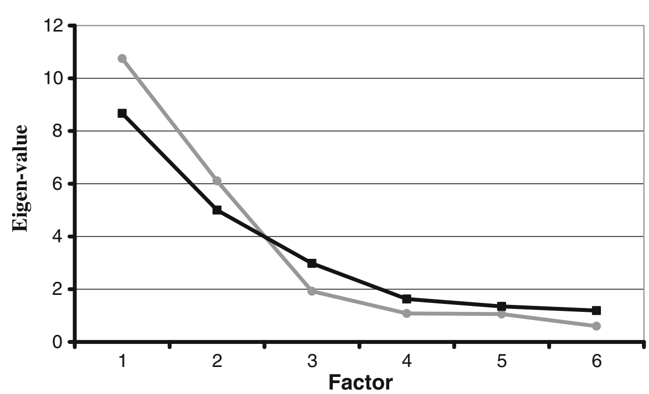

Fig. 4 Factor analysis of the cardiovascular data. Scree plots of eigenvalues for younger (*gray*) and older (*black*) adults

blood vessels and lowered sensitivity of aortic and carotid baroreceptors with increasing age [21, 42]. Hence, parasympathetic neurons in the medulla cannot quickly detect the subtle increases in BP and compensate it with an HR decrease via the baroreflex mechanism. Consequently, SBP may remain permanently enhanced under cognitive load [43].

The age-related equivalence in HF-HRV reactivity in our study contrasts with the data by Uchino et al. [22] who found both an increase in SBP reactivity and a decrease in HF-HRV reactivity in older participants relative to younger ones. The pattern when sympathetic activation (i.e. SBP increase) goes along with parasympathetic withdrawal (HF-HRV decrease) has been interpreted as “reciprocal activation mode” that provides forced resource mobilisation necessary for coping with stress [14]. Notably, the experimental procedure by Uchino et al. [22] was more stressful than that applied in our study. Firstly, they imposed time pressure when ten serial subtractions had to be completed in 1 min. Secondly, the competition between their participants was induced by a comparison of performance between the participants.

In extension to other studies, our data emphasise an important role of baroreflex as a putative mechanism that mediates interactions between sympathetic and parasympathetic systems. The mechanism seems also to mediate different patterns of cardiovascular reactivity in older and younger adults (Fig. 2). In younger adults, the increase in baroreflex under low WM load was accompanied by an increase in HR and a decrease in HF-HRV. The baroreflex increase suggests that younger participants enhanced the “alertness” of their cardiovascular systems already under low WM load to produce preventive resources mobilization as the increase in mental load was expected. As a result, younger adults accelerated their HR with increasing WM load while SBP remained stable. By contrast, the preventive cardiovascular mobilization in older adults was not observed. This could be the reason why they responded to a further increase in WM load with both sympathetic activation and vagal withdrawal (i.e. decrease of baroreflex and HF-HRV as well as the increase of HR and SBP). Yasumasu et al. [19] reported a similar inhibition of the baroreflex which was accompanied by enhancement of SBP and HR during performance of serial arithmetic tasks under time pressure. Apparently, such a “stress” pattern is very resource consuming and may contribute to a decline in performance [14]. In the present study, the pattern was observed in older adults only suggesting their less effective adaptation to WM load as compared to younger adults.

Cardiovascular Recovery

As predicted, we obtained a diminished post-task recovery of baroreflex, HR and HF-HRV in older adults relative to younger ones (Fig. 3), which is in line with other research [23, 24, 26, 29, 32], and our previous data demonstrated a reduced HRV recovery among middle-aged executives as compared to younger ones [30]. In the present study, a larger recovery effect on baroreflex, HR and HF-HRV was associated with better WM performance in younger adults than in older adults. In the study of Wright et al. [29], HR and DBP recovery was related to superior memory performance. Together, these results indicated an important role of parasympathetic control in WM performance with advanced age.

Importantly, SBP in older adults did not return to the baseline after WM load, i.e. they did not show SBP recovery at all. Steptoe and Marmot [32] examined cardiovascular recovery in a large sample of participants who were of similar age to those who participated in our study. They found that a delayed SBP recovery was associated with a delayed recovery of biochemical parameters (Willebrand factor, factor VIII clotting activity and plasma viscosity), which are indicative of coronary heart decease. Other studies demonstrated that older people with a slower recovery of SBP, DBP and HR had higher scores in anxiety and avoidance coping that may result in enhanced emotional reactivity and exaggerate their cardiovascular problems [38].

Concluding Remarks

There are several limitations of the present study. Firstly, we could demonstrate only marginally significant age group × condition interaction on SBP as age differences in SBP were restricted to the high WM load condition and recovery. A larger sample may increase the statistical power of the interaction effect. Secondly, the post-task recovery of 1.5 min used in the present study could provide information on age differences in the magnitude of the recovery effect but not on the recovery speed. Such information could be of practical relevance, e.g. to establish duration of breaks during cognitively demanding work. In future studies, a longer recovery as well as baseline measures must be conducted.

Ageing studies using *n*-back paradigms usually compared younger adults with adults who were 65 years and older. Moreover, the younger group typically comprised university students, while the older group consisted of retired people [39]. Little is known about WM functioning and cardiovascular activity under WM load in older adults who are still employed. Hence, our data obtained in the sample of older employees appear to be of practical relevance for working life. We showed that moderate WM impairments can also be seen in middle-aged workers who are about 10 to 15 years younger than those participating in the majority of ageing studies. We also demonstrated that older workers attempt to compensate performance decline by increased effort, which leads to enhanced cardiovascular "costs" in terms of increased SBP and the absence of the SBP recovery. The result suggests that older workers may have cardiovascular disease risks when they do not have the opportunity to efficiently allocate WM load or have not enough time to recover from it. Future work is required to examine factors that may reduce WM load and attenuate age effects on cardiovascular functioning. Application of these measurements can provide health assessment criteria for older workers who have to do complex work requiring WM.

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