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Cardiovascular reactivity of younger and older adults to positive-, negative-, and mixed-emotion cognitive challenge

Michael J. Hogan[a,*], Jack E. James[a,b], Tadhg R. McCabe[a], Liam Kilmartin[c], Siobhán Howard[a], Chris Noone[a]

[a] School of Psychology, National University of Ireland, Galway, University Road, Galway, Ireland
[b] Reykjavík University, Reykjavík, Iceland
[c] College of Engineering and Informatics, National University of Ireland, Galway, University Road, Galway, Ireland

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ABSTRACT

Although aging is associated with progressive increases in blood pressure level, previous research has been inconsistent as to whether older adults show greater or lesser cardiovascular reactivity (CVR) to emotion than do younger adults. There is reason to believe that these inconsistencies could be clarified by examining age-related differences in hemodynamic profile revealed by measuring the pattern of cardiac output and total peripheral resistance associated with changes in blood pressure reactivity. Accordingly, the present study examined the performance, CVR, and hemodynamic profile of younger and older adults during encoding and recognition of word pairs involving four valence types: positive, negative, mixed (positive/negative), and neutral word pairs. Results revealed higher baseline blood pressure, increased CVR characterized by a vascular hemodynamic profile, and more rapid recovery (especially during encoding) for older than for younger participants. Results are discussed in light of research and theory on the relationship between aging and cardiovascular health.

1. Introduction

Aging is associated with progressive increases in blood pressure (Starr and Bulpitt, 1996) and increased cardiovascular disease risk (Tunstall-Pedoe, 1991). In addition, research suggests that, compared with younger adults, older adults experience increased blood pressure reactivity to psychological challenge (Faucheux et al., 1983; Garwood et al., 1982; Jennings et al., 1990). However, it appears that older adults do not necessarily show greater cardiovascular reactivity than younger adults in all situations, with some research suggesting that older adults are less reactive to emotional stimuli (Labouvie-Vief et al., 2003; Levenson et al., 1991; Tsai et al., 2000). Because prolonged or exaggerated reactivity to psychological stress contributes significantly to the development of cardiovascular disease (Carroll et al., 2001; Light et al., 1992), further research is needed to better understand the circumstances under which older adults are prone to experience greater reactivity than younger adults.

Some researchers argue that older adults focus more on emotion regulation goals than younger adults, and that this is evidenced by an information-processing bias in older adults, especially in relation to memory for content that is positively valenced rather than negatively valenced (Fernandes et al., 2008; Kennedy et al., 2004; Mather and Carstensen, 2003, 2005; Spaniol et al., 2008). However, findings regarding an age-related positivity bias have been inconsistent (Gruhn et al., 2005).

Although the positivity bias in older adults could serve to buffer physiological reactions to negatively valenced information, some research suggests that regulating negative emotion may itself be cognitively and physiologically demanding. For example, in relation to the cognitive demands of maintaining a positivity bias, older adults who do well on tests measuring cognitive control show greater positivity effects than those doing poorly (Mather and Knight, 2005; Petrican et al., 2008). However, when distracted, and thus less able to engage cognitive resources in the service of emotion regulation goals, older adults no longer show a positivity effect in attention or memory, but instead show a negativity bias (Knight et al., 2007; Mather and Knight, 2005). Also, even when younger and older adults perform similarly on behavioral measures of emotion processing (i.e., when doing valence ratings for emotional pictures) while processing negatively valenced stimuli, recent event-related fMRI research findings suggest that older adults show greater functional connectivity than younger adults between the right amygdala and ventral anterior cingulate cortex (Jacques et al., 2010). This greater functional connectivity in older adults could reflect increased emotional regulation efforts in response to negative emotion.

* Corresponding author.
E-mail address: michael.hogan@nuigalway.ie (M.J. Hogan).

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Questions arise as to the differential effects of emotion processing on younger and older adults' cardiovascular reactivity when considering two distinct strands of cardiovascular research conducted to date: one assessing reactivity in response to active and challenging cognitive tasks (Jennings et al., 1990), which has demonstrated higher cardiovascular reactivity in older adults relative to younger adults; the other assessing cardiovascular reactivity to less cognitively (though more emotionally) challenging situations such as viewing emotional film clips (Tsai et al., 2000). In the absence of specific task demands (e.g., instructions to learn the information presented), and in the absence of an effort to evaluate how much information is actually processed (e.g., in the context of a memory test), there is no way of knowing what study participants are actually doing when viewing a film. Similarly, it is difficult to assess the level of cognitive challenge in other studies of emotion processing and cardiovascular reactivity in younger and older adults, including studies that ask participants to recall autobiographical memories (Labouvie-Vief et al., 2003; Levenson et al., 1991). In the current study, this problem is addressed by placing a consistent cognitive burden on both younger and older adults (i.e., "remember this list of word pairs"), while varying the emotional content of the information presented for learning (i.e., word pairs of neutral, negative, positive, and mixed emotional content).

The large body of research concerned with cardiovascular reactions to stress reflects strong interest in blood pressure reactivity, which is justified in light of the fact that blood pressure level is the single most important predictor of cardiovascular disease (MacMahon, 2000; Prospective Studies Collaboration, 2002). However, although previous studies of emotion processing in older adults included a variety of measurements of cardiovascular function (Labouvie-Vief et al., 2003; Levenson et al., 1991; Tsai et al., 2000), blood pressure responses have not previously been examined in that context. Accordingly, in the present study, we examined systolic (SBP) and diastolic blood pressure (DBP) in addition to heart rate (HR). Furthermore, we examined the key underlying physiological parameters of cardiac output (CO) and total peripheral resistance (TPR), which are known to influence blood pressure level and reactivity. CO is the volume of blood pumped by the left ventricle into the aorta each minute, and the simultaneous measurement of blood pressure and CO makes it possible to derive TPR from the relation, TPR = mean arterial pressure (MAP)/CO (Guyton and Hall, 1997).

Gregg et al. (2002) have proposed a model derived from physiological theory, which explains variations in blood pressure in terms of hemodynamic profile characterized by the dynamic compensatory relationship between CO and TPR. The model takes account of the homeostatic regulation of blood pressure whereby an increase in either CO or TPR tends to be "compensated" by an accompanying decrease in the other variable (Gregg et al., 2002; Guyton and Hall, 1997). This means that blood pressure responses of similar magnitude may be accompanied by markedly different patterns of CO and TPR reactivity, and that marked CO and TPR reactivity can occur with no change in blood pressure (i.e., CO increases and is fully compensated by decreases in TPR and vice versa; Gregg et al., 2002). Independent empirical studies have shown that hemodynamic profile is a more reliable predictor of everyday cardiovascular responses than blood pressure reactivity (Gregg et al., 2005; Ottaviani et al., 2006, 2007).

The terms *myocardial* and *vascular reactivity* have been used to describe responses characterized, respectively, by uncompensated increases in CO (predominance of beta-adrenergic responding) and TPR (predominance of alpha-adrenergic responding) (Gregg et al., 1999). Marked and persistent myocardial responding is believed to increase the risk of cardiovascular disease due to tissue over-perfusion and endothelial damage from shear stress, whereas marked and persistent vascular responding is believed to contribute to impaired vascular contractility and atherosclerosis. Compared to a myocardial profile, a vascular profile is believed to contribute over time to greater increased cardiovascular disease risk (Julius, 1988; Palatini and Julius, 2009). To our knowledge, the present study is the first to examine myocardial and vascular response profiles in the context of emotion processing in younger and older adults.

Taking account of previous research findings, we hypothesized that older adults would have higher baseline blood pressure than younger adults. Second, we hypothesized that, after controlling for baseline blood pressure, older adults would show greater blood pressure reactivity to cognitive challenge than younger adults. Third, we hypothesized that, relative to younger adults, the act of regulating any negative emotion experienced while learning negative- and mixed-emotion word pairs would increase the cognitive and physiological burden of the learning task for older adults (i.e., negative- and mixed-emotion regulation was hypothesized to be relatively demanding). This in turn, would result in increased blood pressure reactivity to negative- and mixed-emotion word-pair learning as compared to positive-emotion and neutral word pairs in the older adult sample relative to younger adults. The alternative hypothesis in this context, based on previous findings that older adults show lower reactivity to emotions during less cognitively challenging tasks, was that older adults would learn negative- and mixed-emotion word pairs with a similar blood pressure response to that observed during the learning of both positive and neutral information. Finally, based on previous research demonstrating increased vascular responding while coping with noxious stimuli (Gregg et al., 2002), we examined whether any lower reactivity observed in older adults to negative-emotion challenges was associated with important changes in hemodynamic profile. More specifically, we hypothesized that older adults would demonstrate increased vascular responding to negative emotion independent of changes in blood pressure.

2. Methods

2.1. Participants

Participants were 33 college students ranging in age from 18 to 26 years ($M \pm SD = 19.93 \pm 3.41$ years; 12 males, 21 females) and 25 older adults ranging in age from 63 to 82 ($M \pm SD = 19.93 \pm 3.41$ years; 9 males, 16 females). Older adults were recruited from active retirement groups in the Galway City region, and were paid 20 euro for participating in the study. College-student participants were given course credit for their participation. Younger and older adults did not differ on years of education ($M \pm SD$ old = 14.4 ± 3.81, $M \pm SD$ young = 15.08 ± 0.66, $t(1, 56) = 1.02$, $p > .05$). While 11 older adults were taking anti-hypertensive medication, none reported a history of heart disease or depression. There were no significant differences in levels of heart rate reactivity, diastolic reactivity, or systolic reactivity between the 11 older adults who were taking anti-hypertensive medications and their non-medicated peers ($ps > .05$). Almost half of the younger adult sample were smokers (48.7%; $M \pm SD$ cigarettes per day = 10.63 ± 5.06), and none of the older adults were smokers. Within the younger adult sample, smokers did not differ significantly from non-smokers in their levels of heart rate, diastolic, or systolic reactivity ($ps > .05$). On average, younger adults and older adults reported drinking alcohol between 2 and 3 times a week, with no significant difference in frequency of alcohol use when the two groups were compared. The majority of older adults (85.7%) and younger adults (87.2%) reported engaging in regular physical exercise over the past year. None of the younger or older adults reported a history of epilepsy or diabetes. Older adults had higher resting SBP compared with younger adults ($M \pm SD$ old = 138.81 ± 3.41, $M \pm SD$ young = 124.66 ± 16.15, $t(1, 56) = 2.60$, $p < .05$), but there were no age-differences in baseline DBP ($M \pm SD$ old = 69.90 ± 9.39, $M \pm SD$ young = 70.79 ± 9.22). Participants had body mass index (BMI) in the normal range for their respective age group ($M \pm SD$ older = 26.66 ± 3.30, $M \pm SD$ younger = 22.39 ± 3.12), but older adults had significantly higher BMI than younger adults, $t(1, 56) = 4.39$, $p < .01$. Compared with younger adults, older adults had higher positive affect ($M \pm SD$ young = 32.43 ± 6.94, $M \pm SD$ old = 35.83 ± 6.79, $t(1, 52) = 2.01$, $p < .05$) and lower negative affect ($M \pm SD$ young = 20.00 ± 7.29, $M \pm SD$ old = 13.16 ± 5.17, $t(1, 52) = 3.99$, $p < .01$), as measured by the PANAS (Watson et al., 1988).

2.2. Measurement apparatus and materials

Psychophysiological testing. Cardiovascular function was measured using a Finometer hemodynamic cardiovascular monitor (Finapres Medical Systems BV, BT Arnhem, The Netherlands), which provides beat-to-beat blood pressure and heart rate measurements using the volume-clamp method first developed by Peñaz (1973). A finger cuff applies pressure equal to arterial pressure and uses infrared photo-plethysmograph to detect changes in the diameter of the arterial wall. Measurements are analyzed using the pulse contour method performed by the "Modelflow" program developed specifically for deriving estimates of CO and TPR (Wesseling et al., 1993). The Finometer has been shown to accurately assess absolute blood pressure in healthy persons (Schutte et al., 2003) and in cardiac patients (Guelen et al., 2003), as well as satisfying the validation criteria of the Association for the Advancement of Medical Instrumentation (1987). All testing took place in the same laboratory, and the researcher was present in the room throughout the procedure, with researcher and participant separated by a screen.

Psychometric testing. The PANAS (Watson et al., 1988) was used to measure positive (PA) and negative (NA) emotion. The scale consists of 20 adjectives describing different moods. Ten are described as positive (e.g., "strong") and ten as negative moods (e.g., "upset"). Subjects were asked to indicate the extent to which each adjective described their present feelings on a five-point rating scale from 1 (*Very slightly or not at all*) to 5 (*Extremely*). The internal reliability of scale scores for the sample (n = 74) was good (Cronbach alpha for PA = .87 and for NA = .89).

Experimental task. The experimental task was a word learning task that involved four discrete phases, during which encoding and recognition blocks for positive, negative, mixed (positive/negative), and neutral word pairs were presented. Emotion words presented in each block were derived from the PANAS-Expanded Form (Watson and Clark, 1985), which is composed of 60 words, 30 of which are positive-emotion words and 30 of which are negative-emotion words. Due to the need for a relatively large number of stimuli, synonyms of these words were also used (e.g., Sad/Mournful; Excited/Exhilarated). Word pairs across all four conditions were matched on written frequency in the English language according to the norms provided by Kucera and Francis (1967; mean frequency = 19.34, SD = 21.89). Positive, negative, mixed, and neutral words did not differ significantly on arousal ratings, as indicated by available norms provided by Bradley and Lang (1999; mean arousal ratings = 5.10, 5.66, 5.57, and 3.99, respectively). All words were presented via computer screen in black font color against a white background in Arial style font, size 60.

2.3. Procedure

Ethical approval was granted by the NUI, Galway Research Ethics Committee. Upon arrival to the laboratory all participants read and signed the consent form and completed health, demographic, and PANAS questionnaires. Participants were then moved to the Finometer testing room. Participants were seated in a comfortable chair at a desk with a personal computer and some writing space. The Finometer was attached to the middle finger of the participant's non-dominant hand. Participants were then given 30 min to acclimatize to the laboratory situation. Reading material was supplied in order to facilitate genuine relaxation and the establishment of cardiovascular baselines, by offsetting the risk of rumination-related arousal (Jennings et al., 1992). Following this acclimatization period, participants were asked to put aside their reading material and formal baseline measurements were taken over a 10-min period while participants were at rest. Participants were then given 3-min practice trials to familiarize them with the response requirements of each of the encoding and recognition phases of the learning task. Participants were then required to complete a 24-min experimental learning task.

During the learning task participants were presented with four blocks of word pairs to learn: positive, negative, mixed, and neutral (control) word pairs. During the encoding phase of each block, participants were presented with 30 word pairs. Each word pair was presented on screen for 3000 ms. Participants were asked to read and remember each word pair. Additionally, to ensure attention to all stimuli, participants were asked to press one of two keys to indicate whether or not the letter 'a' was present in either or both of the words presented on screen. Reaction times and accuracy levels were recorded. Each encoding phase lasted for 90 s. This was followed by a 90-s rest period before the recognition test phase began.

During the recognition phase, 30 word pairs were presented. Fifty percent of these word pairs had been presented in the encoding phase; the remaining 50 percent were previously unseen. Memory for the word pairs was assessed by asking participants to respond by pressing the Y-key on the keyboard if they believed they had previously seen the word pair in the encoding phase, or the N-key if they believed the word pair was new. Reaction times and accuracy were recorded. This was followed by a 90-s rest period before the next encoding phase began. Memory performance was computed by subtracting the number of "false alarms" from the number of "hits" divided by the total number of possible hits and converted into a percentage. Order of presentation of blocks was counterbalanced across participants. Beat-by-beat cardiovascular parameters were recorded automatically throughout the 37-min procedure, and were later exported to produce second-level readings from which minute-level mid-phase averages for each of the experimental phases were computed. Specifically, for each of the 16 experimental phases (4 emotion × 2 encoding/recognition × 2 activity/rest) we computed averages for each cardiovascular parameter across the middle 4 × 15 s in the 90 s epoch. Cronbach's alpha was computed for each cardiovascular parameter for each of the 16 experimental phases for both younger and older adults separately and results suggested excellent measurement reliability (Cronbach's alpha range = .92–.98). Baseline cardiovascular measures were computed as the average of 5 × 1-min recording, specifically, minutes 3–7 of the baseline period. SBP, DBP, and HR reactivity for each experimental phase was computed by subtracting baseline means from phase means.

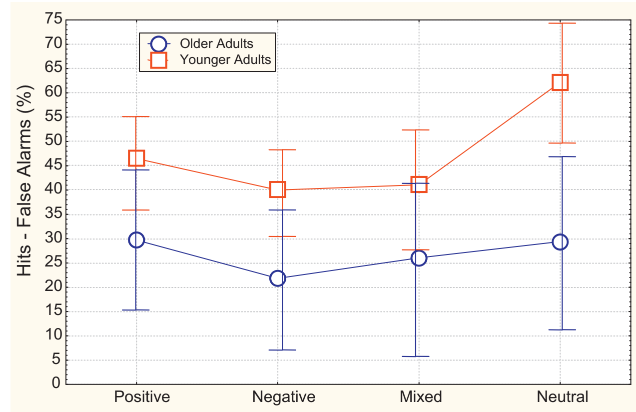

Fig. 1. Memory performance of younger and older adults in response to positive, negative, mixed emotion and neutral word pairs.

Minutes 3–7 were also used to determine baseline CO and TPR for inclusion in the computation of compensation deficit and hemodynamic profile using the method described by Gregg et al. (2002) derived from the known relation, CO × TPR = MAP. Positive scores for compensation deficit signal an increase in blood pressure, and occur when an increase in either CO or TPR is accompanied by a smaller decrease, no change, or an increase in the other variable. Conversely, negative scores for compensation deficit signal a decrease in blood pressure, and occur when a decrease in either CO or TPR is accompanied by a smaller increase, no change, or a decrease in the other variable. Positive scores for hemodynamic profile indicate a myocardial pattern of reactivity, whereas negative scores indicate a vascular pattern of reactivity.

2.4. Statistical analyses

A series of four 2 (age: young, old) × 4 (emotion: positive, negative, mixed, neutral) mixed factorial ANOVAs were run to examine performance differences (speed and accuracy) during both encoding and recognition phases. Additional ANCOVAs were run entering positive (PA) and negative affect (NA) as covariates in the analysis of performance differences. Eight 2 (age: young, old) × 4 (emotion: positive, negative, mixed, neutral) × 2 (phase: encoding, recognition) × 2 (task: activity, rest) mixed ANCOVAs were conducted to examine differences in measures of physiological reactivity across groups and task phases. The covariate used in each case was the baseline (pre-task) measure of the parameter analyzed. In the case of measurements of compensation deficit and hemodynamic profile, two baseline covariates were used: cardiac output and total peripheral resistance. In order to examine the influence of self-reported emotional state on cardiovascular outcomes, additional ANCOVAs were run including PA and NA as covariates. The effects of PA and NA are reported below only where they significantly altered main or interaction effects. As all ANCOVAs included more than two repeated-measures levels, sphericity assumptions were tested using Mauchley (W) tests, with degrees of freedom adjusted using Greenhouse–Geisser corrections (ε) where sphericity assumptions were not met.

3. Results

Table 1 shows descriptive statistics for RT measures. Memory performance is illustrated in Fig. 1. Tables 2 and 3 show descriptive statistics for all physiological measures for younger and older adults across the four emotion processing conditions.

3.1. Cognitive performance

Encoding accuracy and reaction time. There was a main effect of age on encoding accuracy, $F(1,56) = 7.70$; $p < .01$, with younger adults (M = 94.31%) having higher levels of accuracy compared to older adults (M = 90.33%). There was a main effect of age on encoding RT, $F(1,56) = 68.32$; $p < .001$, with younger adults (M = 1.01 ms)

Table 1
Mean (SD) RT for younger and older adults during encoding and recognition of positive, negative, mixed valence and neutral word pair lists.

	Encoding		Recognition	
	Younger	Older	Younger	Older
Positive	1.00	1.30	1.09	1.39
	(0.18)	(0.22)	(0.18)	(0.22)
Negative	0.98	1.25	1.08	1.36
	(0.21)	(0.21)	(0.15)	(0.25)
Mixed	1.03	1.31	1.08	1.42
	(0.19)	(0.21)	(0.17)	(0.26)
Neutral	1.05	1.38	1.01	1.41
	(0.18)	(0.23)	(0.14)	(0.23)

responding faster than older adults ($M = 1.33$ ms). There was a main effect of emotion, $F(3,168) = 10.72$; $p < .001$, with longer RTs to neutral word pairs ($M = 1.22$ ms) relative to mixed (1.17 ms), negative (1.11 ms), and positive words (1.14 ms; $p < .01$ for all three comparisons). Participants also took longer to respond to mixed emotion words relative to negative emotion words ($p < .01$).

Recognition RT. There was a main effect of age, $F(1,56) = 81.57$; $p < .001$, with younger adults ($M = 1.04$) responding faster than older adults ($M = 1.43$). There was an age × emotion interaction effect, $F(3,168) = 3.92$; $p < 01$, with younger adults generally being faster to respond to mixed and neutral relative to positive and negative word pairs, whereas older adults were faster to respond to positive and negative relative to mixed emotion and neutral word pairs. However, post hoc analysis did not reveal any significant pair-wise differences within groups.

Recognition memory. There was a main effect of age, $F(1,55) = 31.21$; $p < .001$, with younger adults having better recognition memory than older adults. In addition, there was a main effect of emotion, $F(3,165) = 6.85$; $p < .01$, with positive and neutral word pairs more accurately recalled than both negative and mixed emotion word pairs. Post hoc analyses revealed significant differences between neutral and both negative and mixed emotion ($p < .001$ for both comparisons), and a significant difference between positive and neutral emotion ($p < .05$). There was an age × emotion interaction effect, $F(3,165) = 2.69$; $p < .05$, with younger adults showing significantly better memory than older adults for neutral word pairs relative to positive, negative, and mixed emotion word pairs ($p < .01$ for all three comparisons; see Fig. 1). Participants did not show better memory for positive emotion words relative to negative emotion words, $F(1, 55) = 3.34$; $p = .07$.

Table 2
Mean (SD) of cardiovascular measures for younger and older adults at baseline and during encoding and recognition of positive, negative, mixed valence and neutral word pair lists.

	Younger adults					Older adults				
	SBP (mmHg)	DBP (mmHg)	HR (bpm)	CO (lpm)	TPR (pru)	SBP (mmHg)	DBP (mmHg)	HR (bpm)	CO (lpm)	TPR (pru)
Encoding										
Baseline	124.66	70.8	75.79	6.3	0.908	136.81	69.91	70.93	5.61	1.079
	(16.16)	(9.22)	(0.42)	(1.27)	(0.205)	(19.3)	(7.4)	(11.78)	(1.35)	(0.28)
Positive	130.23	73.73	75.09	6.38	0.934	149.9	75.12	70.67	5.54	1.188
	(15.15)	(9.14)	(10.64)	(1.23)	(0.217)	(25.21)	(7.59)	(11.82)	(1.29)	(0.348)
Negative	130.2	73.89	75.18	6.43	0.933	148.85	74.59	71.43	5.65	1.162
	(15.23)	(9.13)	(9.98)	(1.3)	(0.22)	(27.81)	(8.79)	(11.92)	(1.42)	(0.34)
Rest	129.93	73.68	75.97	6.48	0.927	147.02	73.13	70.66	5.69	1.13
	(15.99)	(9.7)	(10.5)	(1.44)	(0.235)	(26.55)	(8.19)	(11.1)	(1.48)	(0.34)
Mixed	128.95	73.46	75.45	6.3	0.937	148.5	74.64	71.23	5.67	1.163
	(14.59)	(9.3)	(10.79)	(1.19)	(0.219)	(21.2)	(8.01)	(11.51)	(1.41)	(0.34)
Rest	128	72.91	75.39	6.28	0.934	147.51	73.53	70.34	5.58	1.154
	(15.11)	(9.55)	(9.86)	(1.21)	(0.22)	(24.87)	(7.63)	(11.89)	(1.45)	(0.33)
Neutral	128.83	73.1	74.55	6.26	0.94	152.94	75.67	70.93	5.62	1.18
	(15.15)	(9.43)	(10.72)	(1.25)	(0.23)	(31.49)	(9.07)	(11.28)	(1.42)	(0.34)
Rest	128.12	73.06	75.67	6.32	0.937	147.27	73.52	70.68	5.59	1.152
	(17.69)	(9.77)	(9.01)	(.40)	(0.23)	(30.77)	(10.14)	(11.31)	(1.42)	(0.34)
Recognition										
Baseline	124.66	70.8	75.79	6.3	0.90	136.81	69.91	70.93	5.61	1.079
	(16.16)	(9.22)	(10.42)	(1.27)	(0.20)	(19.3)	(7.4)	(11.78)	(1.35)	(0.28)
Positive	128.04	73.03	74.93	6.25	0.938	146.74	73.57	69.66	5.48	1.166
	(15.99)	(9.21)	(9.69)	(1.18)	(0.212)	(26.63)	(8.22)	(11.84)	(1.29)	(0.33)
Rest	128.26	72.8	76.64	6.40	0.926	139.38	72.74	73.37	5.72	1.090
	(14.26)	(-8.34)	(9.19)	(1.19)	(0.192)	(16.11)	(6.04)	(9.66)	(1.08)	(0.26)
Negative	128.55	72.95	74.58	6.30	0.939	147.04	73.62	69.92	5.55	1.156
	(15.11)	(8.76)	(10.34)	(1.31)	(0.222)	(23.95)	(8.00)	(11.26)	(1.33)	(0.33)
Rest	129.32	73.12	76.91	6.45	0.929	141.40	71.29	69.57	5.76	1.075
	(14.39)	(8.88)	(9.07)	(1.33)	(0.232)	(23.92)	(7.48)	(10. 98)	(1.27)	(0.31)
Mixed	127.67	72.68	75.53	6.23	0.934	148.06	73.94	70.16	5.57	1.164
	(15.23)	(9.36)	(9.44)	(1.06)	(0.213)	(24.52)	(8.04)	(11.20)	(1.38)	(0.34)
Rest	126.9	72.04	77.16	6.18	0.963	140.21	71.14	70.86	5.58	1.105
	(14.3)	(8.26)	(14.08)	(1.02)	(0.24)	(26.77)	(8.37)	(10.51)	(1.36)	(0.30)
Neutral	128.95	73.19	75.10	6.25	0.942	148.08	74.25	69.66	5.49	1.175
	(17.77)	(9.47)	(10.29)	(1.30)	(0.21)	(24.06)	(8.18)	(10.96)	(1.29)	(0.32)
Rest	125.26	72.28	78.48	6.56	0.902	142.84	72.62	71.26	5.60	1.119
	(18.15)	(10.37)	(11.70)	(1.68)	(0.240)	(24.14)	(7.39)	(8.80)	(0.97)	(0.25)

Note. SBP: systolic blood pressure; DBP: diastolic blood pressure; HR: heart rate; CO: cardiac output; TPR: total peripheral resistance.

Table 3
Mean (SD) of compensation deficit (CD) and hemodynamic profile (HP) measures for younger and older adults during encoding and recognition of positive, negative, mixed valence and neutral word pair lists.

	Encoding				Recognition			
	Younger adults		Older adult		Younger adults		Older adults	
	CD	HP	CD	HP	CD	HP	CD	HP
Positive	0.012 (0.012)	0.003 (0.035)	0.025 (0.014)	0.032 (0.047)	0.007 (0.013)	0.01 (0.033)	0.016 (0.017)	0.03 (0.038)
Rest	0.01 (0.015)	−0.008 (0.049)	0.014 (0.018)	0.021 (0.047)	0.003 (0.018)	0.006 (0.041)	−0.002 (0.057)	0.032 (0.06)
Negative	0.012 (0.014)	0.001 (0.037)	0.023 (0.02)	0.02 (0.05)	0.009 (0.015)	0.009 (0.031)	0.017 (0.017)	0.024 (0.044)
Rest	0.011 (0.017)	−0.001 (0.05)	0.015 (0.021)	0.009 (0.044)	0.006 (0.018)	−0.001 (0.043)	0.002 (0.026)	0.02 (0.048)
Mixed	0.01 (0.013)	0.007 (0.037)	0.024 (0.021)	0.02 (0.073)	0.006 (0.012)	0.009 (0.034)	0.019 (0.019)	0.025 (0.05)
Rest	0.007 (0.016)	0.006 (0.04)	0.017 (0.02)	0.023 (0.049)	−0.028 (0.095)	−0.041 (0.144)	−0.015 (0.087)	0.037 (0.143)
Neutral	0.009 (0.014)	0.013 (0.038)	0.028 (0.017)	0.028 (0.037)	0.007 (0.015)	0.014 (0.031)	0.019 (0.013)	0.033 (0.029)
Rest	0.007 (0.016)	0.008 (0.043)	0.016 (0.022)	0.02 (0.036)	0.006 (0.015)	0.008 (0.037)	0.006 (0.016)	0.021 (0.035)

3.2. Cardiovascular responding

Diastolic blood pressure reactivity. There was a main effect of phase, $F(1,56) = 36.51$; $p < .001$, with higher DBP reactivity during encoding (3.40) when compared with recognition (2.47). There was a main effect of task, $F(1,56) = 36.51$; $p < .001$, with higher DBP reactivity during activity (3.48) than during rest (2.39). There was an age × task interaction effect, $F(1,56) = 18.49$; $p < .001$, with older adults showing more of a decrease in blood pressure reactivity from task (4.52) to rest (2.69) than younger adults (2.45–2.10).

Systolic blood pressure reactivity. There was a main effect of group, $F(1,55) = 8.13$; $p < .01$, with younger adults (3.89) demonstrating lower SBP reactivity than older adults (9.55). There was a main effect of phase, $F(1,56) = 42.66$; $p < .001$, with higher SBP reactivity during encoding (8.14) compared to recognition (5.30). There was a main effect for task, $F(1,56) = 46.44$; $p < .001$, with higher SBP reactivity during task (8.10) than during rest (5.34). There was an age × phase interaction effect, $F(1,56) = 11.14$; $p < .005$, with older adults showing more of a decrease in reactivity from encoding (11.70) to recognition (7.40) than younger adults (4.59–3.20). There was an age × task interaction effect, $F(1,56) = 25.22$; $p < .001$, with older adults showing more of a decrease in reactivity from task (11.95) to rest (7.15) than younger adults (4.26–3.53). There was an age × phase × task interaction effect, $F(1,56) = 4.71$; $p < .05$, with older adults showing the steepest drop-off in SBP reactivity from task to rest in the recognition phase. The main effect of age was abolished when BMI was entered as a covariate, $F(1,55) = 2.33$; $p > .05$; however, all interaction effects remained significant.

Heart rate reactivity. There was a main effect of task, $F(1,56) = 16.20$; $p < .001$, with higher HR relative to baseline during the rest phase (0.33) than during the activity phase (−.60). There was an age-group × task interaction effect, $F(1,56) = 7.03$; $p < .01$, with younger adults showing greater change in HR reactivity from task (−.73) to rest (.82) relative to older adults (−.47 to −.14). This effect became non-significant when BMI was entered as a covariate in the analysis, $F(1,57) = 3.36$; $p > .05$. There was a phase × task interaction effect, $F(1,56) = 12.45$; $p < .001$, with no change from activity (−.29) to rest (−.24) observed during the encoding phase, but a significant increase from activity (−.91) to rest (.92) observed in the recognition phase ($p < .01$).

Cardiac output. There was a main effect for task, $F(1,56) = 4.86$; $p < .05$, with CO higher during the rest phase ($M = 6.01$) than during the activity phase ($M = 5.93$). There was a phase × task interaction effect, $F(1,56) = 12.45$; $p < .001$, with no change from rest ($M = 5.98$) to task ($M = 5.99$) observed during the encoding phase, but a significant increase in CO from rest ($M = 5.89$) to task ($M = 6.03$) observed in the recognition phase ($p < .01$).

Total peripheral resistance. There was a main effect of phase, $F(1,56) = 5.08$, $p < .05$, with higher TPR during encoding ($M = 1.05$) than during recognition ($M = 1.03$). There was a main effect of task, $F(1,56) = 21.23$; $p < .001$, with higher TPR during task ($M = 1.05$) than during rest ($M = 1.02$). There was an age × phase interaction effect, $F(1,56) = 5.53$; $p < .05$, with older adults showing significantly higher TPR during encoding ($M = 1.16$) than during recognition ($M = 1.13$; $p < .001$), and with younger adults showing no difference ($M = 0.93$ during both encoding and recognition). There was an age × task interaction effect, $F(1,56) = 10.68$; $p < .005$, with older adults showing significantly higher TPR during task ($M = 1.17$) than during rest ($M = 1.12$; $p < .001$), and with younger adults showing no difference ($M = 0.94$ and 0.93 during task and rest, respectively). Entering BMI as a covariate also revealed a main effect of age, $F(1,55) = 4.25$; $p < .05$, with higher TPR in older adults (adjusted mean = 1.06) when compared with younger adults (adjusted mean = .90).

Compensation deficit (CD). There was a main effect of age, $F(1,55) = 5.45$; $p < .05$, with older adults having higher CD (.013) than younger adults (.005). There was a main effect of phase, $F(1,55) = 31.72$; $p < .001$, with higher CD during encoding (.014) compared to recognition (.004). There was a main effect of task, $F(1,55) = 31.77$; $p < .001$, with higher CD during activity (.015) compared to rest (.004). There was an age × task interaction, $F(1,55) = 5.13$; $p < .05$, with older adults showing more of a change from task (.021) to rest (.006) than younger adults (.009–.002). There was an emotion × phase interaction effect, $F(3,165) = 3.31$; $p < .05$, with the largest reduction in CD from encoding to recognition being observed for mixed emotion. When BMI was entered as a covariate, the main effect of age was not significant; $F(1,53) = 3.49$; $p > .05$.

Hemodynamic profile. There was a main effect of age, $F(1,55) = 5.61$; $p < .05$, with older adults scoring higher (.025) than younger adults (.002). There was a main effect of task, $F(1,55) = 4.96$; $p < .05$, with higher scores during task (.017) than during rest (.009). No other main or interaction effects were observed.

4. Discussion

The present study examined behavioral and cardiovascular responses in younger and older adults during the encoding and recognition of positive, negative, mixed emotion and neutral word pairs. Consistent with our first hypothesis we found that older adults had higher baseline blood pressure than younger adults. We also found evidence in support of our second hypothesis. After controlling for baseline blood pressure, older adults showed greater blood pressure reactivity to cognitive challenge than younger adults. Our third hypothesis was not confirmed. Specifically, we did not find increased blood pressure reactivity in older adults relative to younger adults in response to negatively valenced and mixed-valence word pairs compared to positively valenced and neutral word pairs. Finally, older adults did not demonstrate an increase in vascular responding unique to negatively valenced information. However, unlike the pattern of blood pressure reactivity in the younger adult sample, which was "mixed" (i.e., neither cardiac nor vascular responses predominated), the increased blood pressure reactivity observed in older adults was principally vascular in nature in that a vascular profile was evident for the older adults across all experimental conditions. We also observed higher systolic blood pressure reactivity in older adults relative to younger adults during encoding compared to recognition, and a larger decrease in systolic blood pressure in older relative to younger adults during the rest periods that separated each of the eight encoding and recognition task periods (i.e., older adults were more reactive).

Present findings are consistent with previous research in showing higher blood pressure reactivity in older adults compared with younger adults in response to cognitive challenges (Jennings et al., 1990). The higher mean compensation deficit value for older adults during task performance confirms the presence of age-related increases in reactivity to cognitive challenge. Importantly, the increased reactivity of older participants was found to be characterized by a more pronounced vascular hemodynamic profile. Although the present study is the first to examine age differences in hemodynamic profile in response to positive-, negative-, and mixed-emotion cognitive challenge, the increased vascular profile we observed in older adults is consistent with previous research reporting a normative increase in total peripheral resistance with age (Sathyaprabha et al., 2008). In the current study, the tendency towards homeostatic regulation of blood pressure, whereby an increase in CO in response to challenge is compensated by a decrease in TPR (Gregg et al., 2002; Guyton and Hall, 1997), was less evident in older adults than for younger adults. The older adults in our study had higher TPR during every phase of the experiment (baseline, task, and rest). The increased vascular responding of older adults in the current study is indicative of likely increased risk associated with age-related declines in cardiovascular function (Julius, 1988; Palatini and Julius, 2009).

Consistent with research findings suggesting that emotion regulation skills improve with age in adulthood (Carstensen et al., 1999), older adults in the present study reported lower levels of negative affect and higher levels of positive affect than younger adults, as measured using the PANAS. It should be noted that the older adults who participated in the current study had relatively high educational attainment, were healthy and living independently in the community, and were members of active retirement groups. As such, it is unclear to what extent the high levels of positive affect that were observed are representative of the older adult population generally.

At the same time, we did not find evidence in support of the hypothesis that older adults show a positivity bias in their memory for positive relative to negative information. Notably, the memory task used in the present study differed from the memory tasks used in a number of previous studies that have demonstrated positivity effects for older adults' memory. We assessed memory for word pairs in a paired associates learning task, whereas a number of previous studies in this area assessed autobiographical memory and memory for pictures (Charles et al., 2003; Kennedy et al., 2004; Mather and Carstensen, 2003). Nevertheless, it should be noted that failure to report positivity bias in older adults has been reported previously, particularly for word memory tasks (Gruhn et al., 2005). Furthermore, while older adults in the present study reported higher levels of positive affect (PA) than younger adults, entering PA as a covariate in the analysis of the effects of age, task, phase, and word valence on cardiovascular reactivity, did not alter the effects of age on cardiovascular reactivity.

Consistent with previous findings suggesting that encoding processes are more resource demanding than retrieval processes (Anderson et al., 1998; Iidaka et al., 1999; Naveh-Benjamin et al., 1998), we observed increased cardiovascular reactivity in older adults when encoding word pairs than when recognizing word pairs. Moreover, in light of the requirement to divide attention between learning word pairs and responding to the lexical properties of words, the cognitive control or resource demands during the encoding phase may have been more physiologically demanding for older adults compared with younger adults. Thus, although our intention was to examine the effects of emotion on cardiovascular reactivity, the differential effects of aging on cardiovascular reactivity during encoding and retrieval phases suggests that these effects may have been confounded with the cognitive demands of the task. Having said that, the recognition phase of the task did not require divided attention demands and we did not observe any differential effects of emotion on cardiovascular reactivity in younger and older adults. Future research in this area should seek to manipulate directly both the emotional valence and cognitive difficulty/complexity of tasks in an effort to understand the independent and combined influence of both manipulations on cardiovascular reactivity in younger and older adults.

Notably, a recent meta-analysis of 31 laboratory studies by Uchino et al. (2010) examined if older adults showed lower or higher cardiovascular reactivity compared with younger adults. Consistent with the results of the current study, the results of the meta-analysis revealed that age was associated with lower heart rate reactivity but higher systolic blood pressure (SBP) reactivity during emotionally evocative tasks. Uchino and co-workers also reported that age-related effects for SBP were moderated by the degree of task activation. Specifically, larger effect sizes were observed for emotionally evocative tasks that resulted in a higher level of SBP changes. These results were interpreted by Uchino et al. (2010) in light of the prediction of dynamic integration theory (DIT; Labouvie-Vief et al., 2010), which proposes that, due to diminishing resources, older adults are more likely to show decrements in regulating physiological, emotional, and cognitive functions in the context of high arousal. However, the emotionally evocative tasks selected for inclusion in the meta-analysis by Uchino and co-workers ranged from passive cold pressor tasks, to viewing films and photographs, to performing digit symbol, arithmetic, and speech tasks. Therefore, although age-related increases in SBP reactivity have been consistently observed across a variety of tasks, and although these effects may be larger for tasks that are more activating in general, a deeper understanding of age-related differences in cardiovascular reactivity to emotional challenge suggests that future research should attempt to control a larger number of variables than were incorporated in the present study.

Specifically, future research should examine the impact of individual difference variables (e.g., cognitive ability, coping style, personality, attachment style) and experimental context (e.g., valence and arousal of stimuli and cognitive load associated with the task demands) on age-differences in cardiovascular reactivity to emotional challenge. Although the current study manipulated the valence of words and sought to examine age-differences in cardiovascular reactivity during both encoding and recognition phases while controlling for baseline levels of positive and negative affect, the paradigm used in the current study could be improved. For example, although manipulations of word valence have been used as a method of mood induction with older adults (Knight et al., 2002) and patterns of cardiovascular reactivity have been shown to vary in the context of valence manipulations in verbal recall tasks (Kop et al., 2011), additional research is needed to examine the key features of verbal encoding and recognition tasks that differentially influence cardiovascular reactivity in younger and older adults. We assumed, based on available normative data (Bradley and Lang, 1999), that significant valence differences between positive and negative word pair lists would manifest as significant differences in the interpretation of positive and negative word pair lists. However, it appears that any such differences, if they were present, had no significant effects on cardiovascular reactivity in younger and older adults. One limitation of the current study that needs to be addressed in future research is the failure to directly measure participants' ratings of word valence and arousal. Bradley and Lang (1999) have published norms for word valence and arousal derived from judgments made by young adults, but it is possible that the words used in the current study would have been rated differently by younger and older adults along the valence and arousal dimensions.

Also, it is possible that arousal is a more critical variable than valence in the context of understanding age-differences in cardiovascular reactivity to words. Research by Keil and Freund (2009) indicates that high levels of arousal are judged as more negative by older adults, a relationship that appears to hold for both words and pictures. Keil and Freund argue that the correlation of emotional arousal and negative valence suggests that high arousal is experienced as negative by older adults. More specifically, Keil and Freund argue that, with increasing age, the regulation of physiological systems may become more difficult and deviations from optimal activation levels might last longer in older as compared with young adults when encountering highly arousing stimuli, and such deviations might be experienced as aversive (Duffy, 1962; Lindsley, 1957). Again, manipulating both valence and arousal of stimuli in future research will help to elucidate the independent and combined effects of these variables on cardiovascular reactivity in younger and older adults. Furthermore, in light of the research conducted by Keil and Freund (2009) future research in this area could seek to measure participants' ratings of stimulus valence and arousal directly and not rely upon normative ratings as was done in the current study. This recommendation applies to the use of both verbal and visual stimuli, and in the context of future research efforts to compare verbal and visual emotion processing, it would be important that standardized protocols be developed to measure valence and arousal of stimuli in such a way that allows for reliable and valid comparisons across studies. But care should also be taken to analyze the impact of recording younger and older adults' judgments of stimulus valence and arousal, for example, on subsequent levels of cardiovascular reactivity, as explicitly judging and rating stimuli may alter their functional impact (Barnes-Holmes et al., 2001).

Another limitation of the current study was the failure to control for certain potentially influential variables. For example, although the younger and older adults did not differ on education, alcohol consumption, levels of physical activity, it is notable that none of the older adults were smokers, whereas approximately half of the younger adults were regular smokers. Having said that, within the younger adult sample, smokers did not differ significantly from non-smokers in their levels of heart rate, diastolic, or systolic reactivity. Participants in the current study were not asked to abstain from eating breakfast or lunch, or to refrain from their usual intake of tea or coffee. We did not want participants to be distracted by hunger during the experiment, and caffeine withdrawal is known to interfere with psychomotor and cognitive performance (James and Rogers, 2005). However, failure to control these variables may have also increased the amount of error variance in the current study, which could explain the null effect of valence manipulations on cardiovascular reactivity. Future research in the area should seek to include tighter controls in this regard.

Another potential confound in the current study is the unmeasured variance associated with circadian arousal. Although approximately half of the younger and older adults were tested in the morning, from 11 am to 1 pm, with the other half tested in the afternoon from 2 pm to 4 pm, we did not record testing times and thus could not analyze effects due to circadian variation. Importantly, younger and older adults have different time-of-day preferences (e.g. Intons-Peterson et al., 1999; May and Hasher, 1998; May et al., 1993). For cognitive and physical activities younger adults prefer the afternoon or evening, while older adults prefer the morning, with as few as 2% of older adults reporting an evening preference (Yoon et al., 2006). These preferences have implications for performance. The circadian patterns of arousal that are associated with predictable peaks and declines in body temperature, heart rate, and hormone secretion across the day (Dijk and Czeisler, 1993; Dijk et al., 1999; Horne and Ostberg, 1977) are correlated with corresponding peaks and declines in cognitive performance (e.g. Folkard, 1983; Bodenhausen, 1990; May et al., 1993; Petros et al., 1990). Older adults also show a larger relative performance decrement associated with non-optimal times of day (defined by reference to time-of-day preferences) than do younger adults (see Hasher et al., 2000 for a review). Although there is no evidence for age-differences in cardiovascular reactivity as a result of circadian arousal, it is possible that these differences were present in the current study and it is possible that these differences interacted with the valence manipulations or introduced error variance that could explain the null effect of valence manipulations on cardiovascular reactivity. Because a minority of older adults report an evening preference (Hasher et al., 2000), it is difficult to examine interactions between time-of-day preferences (morning versus evening) and time of testing on age-differences in performance. Nevertheless, future research should attempt to examine the impact of circadian arousal on cardiovascular responses to emotion, or control the influence of circadian arousal by testing younger and older adults during their preferred time of day only. Therefore, while the current study adds to the existing literature in many ways, for example, by highlighting the underlying hemodynamic mechanisms that influence cardiovascular reactivity; by seeking to manipulate, for the first time, valance of stimuli during cognitive challenge in the comparison of younger and older adults cardiovascular responses; by highlighting differential effects of encoding and recognition on younger and older adults' cardiovascular responses; and by illustrating that age-group differences in positive affect (PA) and negative affect do not alter the effects of age on cardiovascular reactivity to challenge, there are a number of limitations to the current research that can be remedied in future research.

More generally, self-regulatory differences in adulthood are superimposed on basic age-related differences in biological activity and reactivity (Lakatta, 1993; Uchino et al., 2005) and thus the synthesis of research findings and effects across levels of analysis is a major challenge for ongoing theory construction in the area. For example, the commonly observed decreases in age-related heart rate reactivity appear to reflect an age-related decrease in the concentration and sensitivity of myocardial beta-adrenergic receptors, possibly linked to an age-related increase in cardiac sympathetic nervous system activity (Bertel et al., 1980; Seals and Esler, 2000). As such, any effects of stimulus processing (e.g., valence, arousal), cognitive demand, and self-regulatory or coping ability is superimposed on a more basic change in cardiovascular responsivity associated with aging, and the use of heart rate as an index to make inferences about how older adults respond to emotionally evocative challenges is difficult without relevant comparison conditions (e.g., activating tasks with less of an emotional component) and complementary assessments (e.g., appraisals). Similarly, age-related increase in blood pressure reactivity reflect a complex array of underlying differences in both neural–receptor processes and structural differences in the aging cardiovascular system, including decreased vascular compliance, decreases in nitric oxide (an important contributor to vasodilation), as well as decreased responsiveness of blood vessels to adrenergic agonists (Palatini and Julius, 2009). Thus, better understanding of the effects of different stimuli, cognitive demands, and self-regulatory capacities on age differences in cardiovascular reactivity will entail a more detailed analysis of the effect of these variables not only on the critical cardiovascular reactivity outcome measures but also their underlying physiological mechanisms.

In conclusion, while the results of the present study are consistent with previous research in suggesting that cardiovascular reactivity in adulthood increases with age, we also confirmed earlier suggestions that age-related increased reactivity appears to be associated with a more pronounced vascular hemodynamic profile. Further research is needed to examine the independent and combined effects of emotion processing and task difficulty on patterns of cardiovascular responding. The inclusion of hemodynamic profile measures in future research will also help to advance our understanding of how homeostatic regulation of blood pressure is achieved in younger and older adults and the role that the emotion regulation skills of older adults may have for homeostatic regulation in the context of cognitive challenge.

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