Gomez, P.; Filippou, D.; Pais, B.; von Gunten, A.; Danuser, B. **Breathing and affective picture processing across the adult life span.** Biological Psychology 119: 101-111, 2016.

Postprint version	Final draft post-refereeing
Journal website	http://www.sciencedirect.com/science/journal/03010511
Pubmed link	http://www.ncbi.nlm.nih.gov/pubmed/27417701
DOI	10.1016/j.biopsycho.2016.07.011

Breathing and affective picture processing across the adult lifespan

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Abstract

The present study investigated differences between healthy younger, middle-aged, and older adults in their respiratory responses to pictures of different valence and arousal. Expiratory time shortened and end-tidal PCO_2 decreased with increasing arousal in all age groups; yet, compared to younger adults, older adults' overall change from baseline was smaller for expiratory time and larger for end-tidal PCO_2. Contrary to their younger counterparts, older adults' inspiratory time did not shorten with increasing arousal. Inspiratory duty cycle did not covary with affective ratings for younger adults, increased with unpleasantness for middle-aged adults, and increased with arousal for older adults. Thoracic breathing increased with increasing unpleasantness only among older adults. Age had no effects on mean inspiratory flow and minute ventilation, which both augmented as arousal increased. We discuss how age effects on respiratory response magnitude and pattern may depend on age-associated biological changes or reflect age-related differences in emotional processing.

Keywords: age-related differences, affective pictures, arousal, valence, respiration, end-tidal carbon dioxide concentration

Breathing and affective picture processing across the adult lifespan

Much of what we know about our capacity to react to emotional events is based on studies with college-aged adults (Lench, Flores, & Bench, 2011). Few studies have examined how middle-aged and older adults react physiologically to affective stimuli under well-controlled laboratory conditions, and whether their reactions differ from those of younger adults.

The present study investigates age-related differences in the response behavior of breathing to series of affective pictures from a dimensional perspective of emotion. Breathing (dys)regulation has widespread physiological and psychological causes and effects (e.g., Courtney, 2009; Ramirez, 2014; Vlemincx, Abelson, et al., 2013). However, psychophysiological investigations of affect include indices of respiratory activity less often than other physiological measures, and analyses are most of the time confined to respiratory rate (RR) and tidal volume (V_T) (Kreibig, 2010). RR and V_T provide only partial insight into the underlying mechanisms of respiratory control. A more detailed breathing analysis includes inspiratory time (T_I), expiratory time (T_E), total breath duration (T_{TOT}, the reciprocal of RR), inspiratory duty cycle (T_I/T_{TOT}), V_T, mean inspiratory flow (V_T/ T_I), minute ventilation (V'_E = RR x V_T ~ V_T/T_I x T_I/T_{TOT}), and measures of the thoraco-abdominal balance such as the percent of rib cage contribution to V_I (%RC) (Boiten, Frijda, & Wientjes, 1994). V_T/T_I is considered to be an index of the intensity of the central inspiratory drive mechanism, which determines the intensity of the inspiratory stimulus, and T_I/T_{TOT} reflects the periodicity of the phase-switching mechanism, which initiates and terminates inspiration (Wientjes, 1992). Moreover, the partial pressure of carbon dioxide at the end of expiration ($P_{et}CO_2$) is an acceptable approximation of arterial PCO_2 values and an index of the equilibrium between ventilation and metabolic demands (Wilhelm, Alpers, Meuret, & Roth, 2001). If ventilation is too high in relation to the rate of CO_2 production (hyperventilation), arterial CO_2 and consequently $P_{et}CO_2$ fall.

The affective dimensions of valence and arousal define fundamental motive systems activated in response to stimuli, one appetitive, associated with positive valence and approach motivation, and the other defensive, associated with negative valence and aversive motivation. Arousal reflects the vigor of motivational mobilization (Bradley & Lang, 2007). In samples of young adults, skin conductance, heart rate, facial muscle activity, brain activity, and startle reflex eyeblink magnitude have been shown to covary with reports of valence and arousal (e.g., Bradley & Lang, 2007). Also breathing varies to some degree along valence and arousal. Overall, respiratory parameters seem to be more consistently related to the arousal dimension than the valence dimension; however, findings are complex and far from conclusive (Boiten, 1998; Boiten et al. 1994; Gomez & Danuser, 2004; Gomez, Shafy, & Danuser, 2008; Gomez, Stahel, & Danuser, 2004; Gomez, Zimmermann, Guttormsen-Schär, & Danuser, 2005; Hempel, Tulen, van Beveren, Mulder, & Hengeveld, 2007; Nyklicek, Thayer, & van Doornen, 1997; Ritz, Thons, Fahrenkrug, & Dahme, 2005; Van Diest et al., 2001; Vlemincx, Vigo, Vansteenwegen, Van den Bergh, & Van Diest, 2013).

We could locate five emotion studies in which age-related differences in RR or respiration depth were analyzed (Kunzmann & Grühn, 2005; Kunzmann, Kupperbusch, & Levenson, 2005; Overbeek, van Boxtel, & Westerink, 2012; Seider, Shiota, Whalen, & Levenson, 2011; Tsai, Levenson, & Carstensen, 2000). Only Tsai et al. (2000) reported an age effect, as older adults (ages 70-85 years) had lower RR than younger adults (ages 20-34 years) during an amusing film clip, but there were no age group differences during a sad film clip. According to these authors, these results may suggest that age-related changes in certain physiological responses may occur for certain emotions induced under specific conditions. To the best of our knowledge, no study on emotion and aging has provided detailed analyses of respiratory behavior as described above.

What seems to emerge from research on emotion and aging is that age-associated changes in physiological reactivity may not be unitary across contexts and measures. Within the limitations of cross-sectional designs, a number of laboratory-based studies provide evidence for age-related differences in cardiovascular reactivity (e.g., Burriss, Powell, & White, 2007; Kunzmann & Grühn, 2005; Overbeek et al., 2012; Seider et al., 2011; Smith, Hillman, & Duley, 2005; Tsai et al., 2000), electrodermal activity (e.g., Burriss et al., 2007), facial electromyographic activity (e.g., Smith et al., 2005), and brain activity (e.g., Kehoe, Toomey, Balsters, & Bokde, 2013; Mather et al., 2004; Smith et al., 2005). Compared to younger adults, older adults showed both blunted (e.g., Burriss et al., 2007; Mather et al., 2004; Smith et al., 2005; Tsai et al., 2000), augmented (e.g., Kunzmann & Grühn, 2005; Seider et al., 2011; Smith et al., 2005), and similar (e.g., Kunzmann et al., 2005; Kunzmann & Richter, 2009; Overbeek et al., 2012) physiological reactivity to affective challenges.

The respiratory system undergoes many changes with advancing age. These include modifications of the chest wall, the lungs, and the respiratory muscles resulting in reduction in chest wall compliance, decrease in strength of elastic recoil of lung parenchyma, enlargement of airspaces, changes in pulmonary vasculature, decrease in respiratory muscle strength, and reduction of lung function. Moreover, age-dependent differences exist in the ventilatory response to hypoxia, hypercapnia, added loading, and exercise (Lalley, 2013; Taylor, 2011). Breathing behavior depends on the interplay of different regulatory mechanisms, including reciprocal interactions between the pontomedullary respiratory network and numerous subcortical and cortical areas that are critically implicated in the generation of emotional states (Ramirez, 2014; Subramanian & Holstege, 2014). The brain activity to emotional stimuli of healthy younger and older adults is different, and these age-related differences appear to depend, to some extent, on the perceived valence and arousal tone of the stimuli (Dolcos, Katsumi, & Dixon, 2014; Kehoe et al., 2013; Nashiro Sakaki, & Mather, 2012). For instance, the amygdala activity to negative vs. positive information is reduced in older adults compared to younger adults, whereas unpleasant stimuli induce greater prefrontal cortex activity compared with neutral stimuli in older individuals than in younger ones (Nashiro et al., 2012). Also, older adults display different arousal-dependent responses than younger adults in a number of cortical regions (Kehoe et al., 2013). To the extent that the activity of brain structures involved both in emotion generation and breathing regulation changes in response to emotional challenges as age progresses, respiratory reactivity to affective stimuli may be expected to vary across ages.

The aim of the present study was to fill a gap in research on the psychophysiology of emotion and aging by examining age-related differences in the respiratory responses to affective pictures adopting the valence-arousal perspective as framework. Age effects on the physiological reactivity to emotional stimuli have been discussed in terms of age-associated differences in magnitude and pattern of physiological responding (Levenson, 2000). The design and analytical approach of the present study were set up in order to clarify whether age influences the “respiratory response magnitude”, defined as the overall respiratory response to the stimuli in terms of magnitude of change from baseline (i.e., decrease/increase), and the “respiratory affective pattern”, defined both as the pattern of breathing responses to specific affective categories (i.e., linear/quadratic trend across pleasant, neutral, unpleasant contents) and as the relationship between self-reported affective ratings and respiratory responses. Four main combinations of response magnitude and affective pattern are theoretically possible in terms of age effects, i.e., i) Age groups do not differ either in their response magnitude or affective pattern; ii) Age groups do not differ in their response magnitude but display different affective patterns; iii) Age groups differ in their response magnitude but do not differ in their affective patterns; iv) Age groups show differences both in their response magnitude and affective pattern. Taking V'_E as an example, an age effect on response magnitude would be that older adults show larger overall increases in V'_E from baseline than younger adults do. An example of age-related difference in the affective pattern would be that younger adults have larger changes in V'_E in response to pleasant and unpleasant vs. neutral contents and a significant negative correlation between V'_E changes and self-rated arousal, whereas older adults do not.

Method

Participants

The sample consisted of 176 participants in three age groups: younger (ages 20-34 years), middle-aged (ages 40-54 years), and older (ages 60-74 years). Studies of aging and emotion often compare young adults with an older sample. With the inclusion of a middle-aged sample nonlinear age effects can be explored. Table 1 reports other sample characteristics. Three additional participants completed the study protocol, but their data were unusable due to procedural flaws. Participants were recruited from the Lausanne area through advertisements placed in different public places, in newspapers and magazines, and on websites. The study was approved by the local ethics committee.

A screening questionnaire was used to include only respondents who: (i) were proficient in French; (ii) had scores lower than 11 on the anxiety and depression scales of the Hospital Anxiety Depression Scale (Zigmond & Snaith, 1983, 14 items, example items “I get sudden feelings of panic”, “I still enjoy the things I used to enjoy”, Anxiety and Depression scale min = 0, max = 21). This was done to avoid the experience of excessive emotional distress among vulnerable people; (iii) reported at least “satisfactory” current general health on a 5-point scale ranging from “very good” to “very bad” ; (iv) were not pregnant or breastfeeding; (v) did not use recreational/illicit drugs; (vi) had normal or corrected-to-normal vision and did not suffer from color blindness; (vii) did not have a cardiac pacemaker; and (viii) were not currently under medical treatment for any psychiatric disorder.

Participants were well-functioning individuals as indicated by several indices (see Table 1). First, anxiety and depression scores were very low. Second, self-reported mental health, physical functioning, and general health perception as assessed with the Medical Outcomes Study 36-Item Short Form were all better than average scores of the general local population (Richard et al., 2000). Finally, participants' mean scores of verbal fluency were above average compared to normative data (Tombaugh, Kozak, & Rees, 1999).

Stimuli

Stimuli were 84 pictures selected from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 2005). They were arranged into 14 series each consisting of 6 different pictures. The series represented different thematic contents, six expected to be pleasant, six unpleasant, and two neutral. The six pleasant contents were appetizing food, erotic heterosexual couples, pleasant family scenes, pleasant nature, romantic heterosexual couples, and sport scenes. The unpleasant contents included environmental contamination, human loss, mutilated/burned bodies, physical violence, sick/injured human beings, and suffering/dead animals. The two neutral series showed household objects and neutral human activities. Sustained exposure to series of several pictures of similar affective and thematic contents was chosen to maximize the respiratory reactivity associated with picture viewing (Gomez et al., 2008). The IAPS numbers of the pictures are given in the Appendix.

Measures

Respiratory measures. The following respiratory measures were assessed on a breath-by-breath basis: *inspiratory time* (T_I), *expiratory time* (T_E), *total breath duration* (T_{TOT}), *inspiratory duty cycle* (T_I/T_{TOT}, an index of inspiratory timing), *inspiratory volume* (V_I), *mean inspiratory flow* (V_I/T_I, an index of inspiratory drive), *minute ventilation* (V'_E), *percent of rib* *cage contribution to* V_I (%RC, a measure of the thoraco-abdominal balance), and *end-tidal* PCO_2 ($P_{et}CO_2$). All parameters except $P_{et}CO_2$ were recorded with the LifeShirt system, a snugly fitting T-shirt using respiratory inductive plethysmography (VivoMetrics Inc., Ventura, California, USA). In a calibration procedure at the beginning of the experiment, ventilation was measured at the same time with the EasyOne spirometer (ndd Medizintechnik AG, Zurich, Switzerland) and the LifeShirt system. Before data was extracted, a two-step calibration was employed. First, we utilized the automatic qualitative diagnostic calibration method, which calibrates the abdominal and thoracic bands using gains calculated within the VivoMetrics program during a 5-min period of natural breathing (Sackner et al., 1989). This was followed by a linear regression performed off-line yielding the regression coefficient to be used for the reconstruction of the volume out of the LifeShirt signals. $P_{et}CO_2$ was measured using a nasal canula connected to a nondispersive infrared CO_2-monitor (Microcap Handheld Capnograph, Oridion Medical 1987 Ltd., Jerusalem, Israel; 50 ml/min flow rate, 40 Hz sampling rate, 1 mmHg resolution). $P_{et}CO_2$ values were stored together with the Lifeshirt parameters. Participants were instructed to breathe through the nose with the mouth closed.

Valence and arousal ratings. Self-reports of *valence* and *arousal* were registered using the pencil-and-paper version of the 9-point Self-Assessment Manikin (SAM, Lang et al., 2005, scale min = 1, max = 9).

Sociodemographic data and self-rated health. A few days prior to the experimental session, participants filled in a questionnaire assessing the following measures: *sociodemographic data* (age, sex, marital status, employment status, educational level); *mental health*, *physical functioning*, and *general health perception* assessed with the Medical Outcomes Study 36-Item Short Form (SF-36, Ware & Sherbourne, 1992, scores between 0 and 100 with higher scores indicating better health).

Verbal fluency. *Verbal fluency* was assessed with the Animal Naming Task (1 minute, Kertesz, 1982). This test shows a strong association with general intellectual ability and has been extensively used with older adults (Lindenberger, Mayr, & Kliegl, 1993).

Voluntary respiratory control. Participants answered the item "During the experiment I voluntarily controlled my breathing" on a 5-point scale ranging from 0 (*not at all*) to 4 (*a lot*).

Procedure

Participants were tested individually in one experimental session lasting approximately 2 hr. First, the experimenter provided the participants with an outline of the experimental procedure and an explanation of the measurements. They were told that 14 series, consisting of 6 pictures each, would be displayed on the screen in front of them. They were also informed that the pictures would depict life events, objects, and persons that could evoke positive and negative emotions. Then, participants filled out an informed consent.

After attaching the sensors and performing the volume calibration of the LifeShirt system, the picture presentation and the self-rating procedure were explained to the participants. It was clearly stated that the ratings should be performed quickly and reflect how they felt while they were looking at the pictures. They were also told to avoid excessive movements (e.g., bending, stretching). Then, participants were shown an exemplary series of images of mushrooms followed by the 14 series, each lasting 1 min (10 s per picture), with 75-s pauses in between. The pictures were displayed on a 19-inch computer monitor placed at a viewing distance of about 70 cm. After each series, participants gave one valence and one arousal rating reflecting their affective experience and then relaxed until the next series.

There were six different presentation orders of the series. These orders were constructed with the constraint that no more than two series of similar valence (positive, negative, neutral) were presented consecutively. Further, we made sure that over the six presentation orders the same series was presented on average both at the beginning, in the middle, and in the final part of the experiment. These orders were counterbalanced across age groups and sex to control for possible within-session habituation or fatigue effects. For each of the six presentation orders of the fourteen series, the six pictures within each series were presented in one specific order. Across the six presentation orders of the series, the same picture was shown in first, second, third, fourth, fifth, and sixth position, respectively.

Upon completing the picture viewing session, sensors were removed, and the participants answered the question about voluntary respiratory control. After a 10-min break, the animal naming task was performed, together with other tasks that are irrelevant to the present report. Finally, the participants were debriefed, paid 100 Swiss francs, and thanked.

Data Reduction and Response Definition

Due to malfunctioning of the connection between capnograph and Lifeshirt system, $P_{et}CO_2$ values were not available for three participants. The breathing curves were analyzed with VivoLogic (VivoMetrics Inc., Ventura, California, USA). The off-line volume calibration was performed by the second author and verified by the first author. The third author and a research assistant, blind to the content of the series and to participants' personal data, visually inspected the $P_{et}CO_2$ curves and extracted breath-by-breath $P_{et}CO_2$ values. Values were scored only for breaths with a distinct plateau (Wilhelm et al., 2001) and were verified by the first author. Specifically, for each breath the $P_{et}CO_2$ value was determined as the level at which $P_{et}CO_2$ stops rising during the nearly horizontal plateau. Furthermore, the respiratory volume and respiratory rate channels were displayed in parallel to aid in judging the $P_{et}CO_2$. Sudden changes in $P_{et}CO_2$ of more than 3 mmHg in one single breath without an obvious change in the respiratory pattern (i.e., depth or frequency) were excluded.

Median values of the respiratory measures were calculated for each participant for the 30-s period before onset of each picture series (baseline) and for the 60-s series. The baseline values were subtracted from the values of the stimulus intervals to compute change scores for each series. These change scores were entered into repeated-measures ANOVAs and linear mixed model analyses Medians instead of means were preferred because the median is a more robust estimate of the center of a data sample (Gomez et al., 2008). The baseline periods did not include the time that participants rated the previous series.

We scored valence and arousal ratings so that higher values indicated *more positive* and *more aroused*, respectively. The variable *voluntary respiratory control* was heavily skewed toward 0 (no respiratory control) and was, thus, dichotomized into *no* (score 0) and *yes* (scores 1 to 4).

Statistical Analyses

All analyses were performed using SPSS Statistics version 22 (IBM Corp., Armonk, NY, USA). An alpha level of .05 was used for all statistical tests.

First, we evaluated differences between age groups in baseline breathing. Mean scores of the fourteen baseline intervals were calculated for each respiratory measure and each participant and subjected to one-way ANOVAs with *Age Group* (3 levels: younger, middle-aged, older) as between-subject factor. Significant age group effects were followed up with pairwise *t* tests with Bonferroni correction.

The second set of analyses assessed psychophysiological reactions as they vary when looking at pleasant, neutral, and unpleasant series by averaging responses over the different series in each a priori valence category (pleasant: appetizing food, erotic heterosexual couples, pleasant family scenes, pleasant nature, romantic heterosexual couples, sport scenes; neutral: household objects, neutral human activities; unpleasant: environmental contamination, human loss, mutilated/burned bodies, physical violence, sick/injured human beings, suffering/dead animals). In these repeated-measures ANOVAs, the respiratory change scores as defined above and valence and arousal ratings were the dependent variables with *Valence Category* (3 levels: pleasant, neutral, unpleasant) as within-subject factor and *Age Group* as between-subject factor. We report Valence Category effects and Valence Category x Age Group interactions of both the linear and quadratic contrasts (e.g., Ritz et al., 2005). For significant Valence Category x Age Group interactions, we tested trends for the three age groups separately and performed Bonferroni-adjusted pairwise comparisons between age groups. For all ANOVAs, we examined the robustness of our findings when adding the predictors *Sex*, *Voluntary Respiratory Control*, *Body Height* (the main anthropometric determinant of lung function, Taylor, 2011), and *Educational Level.*

Finally, linear mixed models with marginal maximum likelihood estimation were calculated for each respiratory variable to investigate age-related differences in the relationships between affective ratings and respiratory responses. The predicted variables were the change scores of the respiratory measures as defined above. First, we tested the model including a random intercept for each participant and fixed effects for the three factors of main interest *valence ratings* V, *arousal ratings* A, and *Age Group* (*Model 1*). V and A are the valence and arousal judgments given by the participants centered around the respective grand mean. Significant effects for Age Group in this model indicate significant differences between age groups in the average level of respiratory reactivity (i.e., response magnitude). Subsequently, we tested three models by adding to Model 1 the V x Age Group interaction (*Model 2*), the A x Age Group interaction (*Model 3*), and both interactions (*Model 4*). These models allowed us to determine whether age had modulatory effects on the relationship between affective ratings and respiratory responses. When one or both interaction terms were significant, the model with V and A was estimated for the three age groups, separately. For respiratory variables for which neither the V x Age Group interaction nor the A x Age Group interaction were significant, only Model 1 is reported. Where appropriate, pairwise *t* tests comparing age groups were performed, and Bonferroni-adjusted *p*-values are reported. *Sex, Voluntary Respiratory Control, Body Height,* and *Educational Level* were additionally included.

Finally, in all analyses, we evaluated residuals in relation to the assumptions of homoskedasticity, normality, and linearity. Overall, the residual analyses indicated good conformity to these assumptions. There were only few outlying observations defined as those scores having absolute standardized residuals greater than 4 (less than 1%), and all analyses were rerun after excluding them to evaluate their impact on the tested models. The results of these analyses are reported if the effects of the predictors in the main analyses were significant and became nonsignificant or vice versa.

Results

Age-related Differences in Baseline Respiration

There were age group differences in the baseline means of %RC and $P_{et}CO_2$. Detailed results are reported in Table 2.

Responses to a priori Valence Categories

Mean changes of the respiratory variables and affective ratings by age group when viewing pleasant, neutral, and unpleasant picture series are given in Table 3.

Respiration.

Valence Category effects. Table 4 shows significant Valence Category effects of the linear and quadratic contracts. There were significant quadratic trends for T_I, T_E, V'_E, and V_I/T_I. Compared to neutral series, T_I and T_E change scores for pleasant and unpleasant series tended to be lower, and V'_E and V_I/T_I change scores tended to be higher for pleasant and unpleasant series. The linear contrasts for T_I/T_{TOT} and %RC change scores were significant with both parameters increasing from the pleasant to the unpleasant series. $P_{et}CO_2$ change scores showed an inverted V-shape with lowest scores for the unpleasant series (significant linear and quadratic contrasts). For T_{TOT} and V_I, no polynomial trends reached significance.

Valence Category x Age Group interactions. For T_I/T_{TOT}, the Valence Category x Age Group interaction of the linear trend was significant, $F(2, 173) = 3.04$, $p = .048$, $\eta_p^2 = .035$. The linear trend was highly significant for middle-aged adults, $F(1, 51) = 8.81$, $p = .001$, $\eta_p^2 = .147$, and to a lesser degree for older adults, $F(1, 59) = 4.33$, $p = .042$, $\eta_p^2 = .068$. On the contrary, for younger adults the linear contrast was not significant. Age groups differed in their T_I/T_{TOT} responses to the pleasant series, $F(2, 173) = 3.47$, $p = .033$, $\eta_p^2 = .039$, with younger adults having higher T_I/T_{TOT} change scores than middle-aged, $t(114) = 2.45$, $p = .048$, $d = 0.45$, and older adults, $t(122) = 2.27$, $p = .075$, $d = 0.41$. There were no age effects for the neutral and unpleasant series.

For %RC, the Valence Category x Age Group interaction of the linear trend was significant, $F(2, 173) = 3.17$, $p = .045$, $\eta_p^2 = .035$. %RC increased from the pleasant to the unpleasant series for older participants, $F(1, 59) = 11.58$, $p = .001$, $\eta_p^2 = .164$, and to a lesser degree for middle-aged participants, $F(1, 51) = 4.93$, $p = .031$, $\eta_p^2 = .088$, but not for younger participants. Age groups differed in their %RC responses to the neutral, $F(2, 173) = 3.36$, $p = .037$, $\eta_p^2 = .037$, and to the unpleasant, $F(2, 173) = 5.35$, $p = .006$, $\eta_p^2 = .058$, series. For the neutral series, younger adults had lower %RC values than middle-aged adults, $t(114) = 2.38$, $p = .057$, $d = 0.45$. For the unpleasant series, younger adults had lower %RC values than middle-aged, $t(114) = 2.40$, $p = .054$, $d = 0.46$, and older, $t(122) = 2.88$, $p = .015$, $d = 0.51$, adults. There were no age differences for the pleasant series. There were no other significant Valence Category x Age Group interactions.

Other modulatory effects. The Valence Category main effect of the quadratic trend for T_I became nonsignificant after taking into account the significant Valence Category x Voluntary Respiratory Control interaction of the quadratic trend, $F(1, 170) = 4.88$, $p = .029$,

η_p^2 = .028. Participants not controlling their breathing showed a significant inverted V-shape across valence categories, *F*(1, 125) = 11.46, *p* < .001, η_p^2 = .084, whereas participants saying to have controlled their breathing did not.

The Valence Category main effect of the linear contrast for $P_{et}CO_2$ became nonsignificant after including the significant Valence Category x Sex interaction of the linear contrast, *F*(1, 171) = 4.58, *p* = .034, η_p^2 = .026. Whereas men showed a significant quadratic trend, *F*(1, 73) = 5.74, *p* = .019, η_p^2 = .073, but not a linear trend, women had a significant linear trend, *F*(1, 98) = 9.21, *p* = .003, η_p^2 = .086, and a quadratic trend approaching significance.

Affective ratings. There were no significant main age group differences over the fourteen series for either valence or arousal ratings.

Valence Category effects. As expected, valence ratings decreased from pleasant to unpleasant series in a monotonic fashion (significant linear trend). On average, pleasant and unpleasant contents were rated as more arousing than neutral contents, and unpleasant series were rated as more arousing than pleasant series (significant linear and quadratic trends).

Valence Category x Age Group interactions. The Valence Category x Age Group interaction of the linear trend for valence ratings was significant, *F*(2, 171) = 5.90, *p* = .003, η_p^2 = .065. This interaction mainly reflected a significant Age Group effect for the unpleasant series, *F*(2, 172) = 5.92, *p* = .003, η_p^2 = .064, and a significant Age Group effect on the difference between valence ratings of the unpleasant and neutral series, *F*(2, 172) = 7.58, *p* = .001, η_p^2 = .081. Older adults gave significantly more negative ratings than younger adults, *t*(121) = 3.73, *p* < .001, *d* = 0.67. Relative to the Neutral series, younger participants gave significantly less negative ratings to the unpleasant series than both middle-aged participants, *t*(114) = 2.76, *p* = .021, *d* = 0.53, and older participants, *t*(121) = 3.85, *p* < .001, *d* = 0.70. The Age Group effect for the pleasant series, the neutral series, and the difference between pleasant and neutral series did not reach statistical significance.

The Valence Category x Age Group interaction of the linear trend for arousal ratings was significant, $F(2, 172) = 3.74$, $p = .026$, $\eta_p^2 = .042$. The three age groups did not differ significantly in their arousal ratings for the pleasant, neutral, and unpleasant series. However, they differed in the difference between arousal ratings of the pleasant and neutral series, $F(2, 172) = 5.39$, $p = .005$, $\eta_p^2 = .059$. Relative to the Neutral series, younger adults reported significantly higher arousal ratings for the pleasant series than middle-aged adults, $t(114) = 2.66$, $p = .027$, $d = 0.49$, and older adults, $t(121) = 3.06$, $p = .008$, $d = 0.55$. The Age Group effect on the difference between arousal ratings of the unpleasant and neutral series was not significant.

Age-related Effects on the Relationships Between Affective Ratings and Respiratory Responses

The estimated models for the nine respiratory measures are presented in Table 5. For T_I, there was a significant Arousal x Age Group interaction (Model 3, see Figure 1). Separate analyses for the three age groups showed that for younger participants, T_I significantly shortened with increasing arousal (valence estimate = 0.003, *SE* = 0.004, *p* = .47; arousal estimate = -0.009, *SE* = 0.004, *p* = .028). Middle-aged adults showed the same tendency (valence estimate = -0.005, *SE* = 0.005, *p* = .34; arousal estimate = -0.011, *SE* = 0.006, *p* = .059). On the contrary, older adults showed no significant relationships between T_I change scores and affective ratings (valence estimate = -0.001, *SE* = 0.003, *p* = .73; arousal estimate = 0.004, *SE* = 0.004, *p* = .29).

For T_E, significant Arousal and Age Group main effects were found (Model 1, see Figure 1). With increasing arousal, T_E shortened, and younger participants had more negative T_E change scores than older participants (mean difference = -0.203, *SE* = 0.074, *p* = .021). For T_{TOT}, the Arousal and Age Group main effects approached significance ($p < .10$).

For T_I/T_{TOT}, the Valence x Age Group interaction and the Arousal x Age Group were significant (Model 4). Separate analyses for the three age groups showed that for younger participants, T_I/T_{TOT} did not covary with either valence (estimate = 0.03, *SE* = 0.06, *p* = .55) or arousal (estimate = 0.08, *SE* = 0.06, *p* = .18). Middle-aged adults showed a significant negative relationship with valence (estimate = -0.26, *SE* = 0.07, *p* < .001) but not with arousal (estimate = -0.08, *SE* = 0.08, *p* = .28). On the contrary, older adults showed a significant positive relationship with arousal (estimate = 0.18, *SE* = 0.08, *p* = .028) but not with valence (estimate = -0.02, *SE* = 0.06, *p* = .74).

V_I/T_I and V'_E significantly increased with increasing arousal, with no significant effects of age. There were no significant effects for V_I.

For %RC, the Valence x Age Group interaction was significant (Model 2, see Figure 1). Separate analyses for the three age groups showed that for younger participants, %RC did not covary with either valence (estimate = 0.01, *SE* = 0.08, *p* = .93) or arousal (estimate = -0.09, *SE* = 0.09, *p* = .32). Middle-aged adults had also no significant linear relationships between %RC change scores and affective ratings (valence estimate = -0.09, *SE* = 0.08, *p* = .26; arousal estimate = 0.08, *SE* = 0.09, *p* = .37). On the contrary, older adults showed a significant negative linear relationship with valence (estimate = -0.24, *SE* = 0.07, *p* < .001) but not with arousal (estimate = 0.08, *SE* = 0.08, *p* = .33).

Finally, $P_{et}CO_2$ change scores significantly decreased with increasing arousal, and there was a significant Age Group main effect (Model 1, see Figure 1). The older group had higher change scores than the younger group (mean difference = 0.53, *SE* = 0.16, *p* = .003) and the middle-aged group (mean difference = 0.40, *SE* = 0.15, *p* = .027). The effects of the covariates Sex, Voluntary Respiratory Control, Body Height, and Educational Level were not significant for any respiratory variables (*p*s > .10).

Discussion

General pattern of respiratory reactivity to the picture viewing task

Attentively looking at pictures was characterized by specific changes in the breathing pattern consisting in shortening of breath cycle and decrease in tidal volume, resulting in mild hypoventilation with slightly augmented $EtCO_2$. Moreover, thoracoabdominal balance shifted towards more diaphragmatic breathing. This pattern is largely in agreement with findings of previous studies on the respiratory response to affective pictures (e.g., Gomez et al., 2004, 2008; Ritz et al., 2005). There ought to be some adaptive benefit conferred by these breathing pattern changes related to the behavioral demands of the task of looking at pictures (i.e., attentive processing and information intake; Boiten et al., 1994; Gomez, 2005; Grossman & Wientjes, 2001; Hughes, 1979).

Age-related differences in respiratory reactivity within the valence-arousal space

Age influenced changes from baseline in T_I, T_E, T_I/T_{TOT}, %RC, and $P_{et}CO_2$. These five variables were not assessed in any previous study on emotion and aging. The age effect for T_E and $P_{et}CO_2$ was a main effect reflecting age group differences in the overall response magnitude. For T_I, T_I/T_{TOT}, and %RC, age had an effect on their affective pattern, i.e., their variations across the affective picture categories and along the affective dimensions. V_I, V_I/T_I, and V'_E appeared to be largely unaffected by age both in terms of response magnitude and affective pattern. Our results for V_I are in line with previous findings (Kunzmann et al., 2005; Seider et al., 2011).

A positive correlation between changes in V'_E and arousal has been one of the most consistently reported finding in research on emotion and breathing with young adults (Boiten, 1998; Gomez et al., 2004; Gomez et al., 2008; Gomez & Danuser, 2004; Gomez et al., 2005). The present study replicates and extends these results by showing that the relationship between V'_E and arousal is age independent, at least in the context of picture viewing. Increasing self-rated arousal was also associated with decreases in $P_{et}CO_2$, suggesting that ventilatory changes during picture viewing did not parallel variations in metabolic activity. This result contrasts with previous findings (Gomez et al., 2008) but is in line with the observation of significantly lower $P_{et}CO_2$ levels during high-arousal affective states as compared to low-arousal states induced with imagery (Van Diest et al., 2001) and hypnosis (Dudley, Ripley, Martin, & Holmes, 1964). According to a feedforward control of breathing from higher centers, increases in V'_E and decreases in $P_{et}CO_2$ with increasing arousal might be best interpreted as preparation for augmented physical activity in support of either avoidance of threats or approach to resources (Van Diest et al., 2001). The correlation between $P_{et}CO_2$ and self-rated arousal was not modulated by age; yet, older adults had higher overall changes from baseline than the other two age groups. We computed the absolute ratio between the average change in $P_{et}CO_2$ and the average change in V'_E from baseline. The mean ratios for the younger, middle-aged, and older adults were 0.2, 0.4, and 0.7 mmHg/[l/min], respectively. This indicates that $P_{et}CO_2$ tended to increase more for a given decrease in V'_E among older participants. This tendency might reflect age-related differences in efficiency of gas exchange associated to differences in ventilation-perfusion heterogeneity and gas diffusing capacity across the alveolocapillary membrane (Brischetto, Millman, Peterson, Silage, & Pack, 1984; Cardus et al., 1997; Lalley, 2013; Neder, Andreoni, Peres, & Nery, 1999).

The age effects on the time parameters were complex. In young adults, T_I/T_{TOT} increased from baseline to a similar degree in response to pleasant, neutral, and unpleasant series and did not vary along the affective dimensions of valence and arousal, in accordance with previous studies using the picture viewing paradigm (Gomez et al., 2004, 2008). On the contrary, for the other two age groups, T_I/T_{TOT} was influenced by the affective tone of the pictures. For middle-aged participants, T_I/T_{TOT} change scores increased from the pleasant to the unpleasant series and positively correlated with self-reported unpleasantness. For older participants, T_I/T_{TOT} change scores increased from the pleasant to the unpleasant series and positively correlated with self-rated arousal. These unique age-related changes in T_I/T_{TOT} resulted from specific changes in T_I and T_E. Shorter T_E for pleasant and unpleasant series compared to neutral series as well as a negative relationship between T_E and self-reported arousal were common to all three age groups. However, the magnitude of change from baseline was a function of age, with younger and older adults showing the largest and smallest shortening, respectively. Quiet expiration is driven by the release of the energy stored in the contracted diaphragm and primarily relies on the elastic properties of the lungs. Due to reduction of the elastic recoil of the lungs with aging (Knudson, Clark, Kennedy, & Knudson, 1977), relatively longer expiration time to exhale air may be required with advancing age.

Age modulated the relationship between self-rated arousal and T_I change scores. In younger adults, T_I behaved like T_E and shortened with self-rated arousal. A more pronounced shortening of the time parameters has been reported to occur in young adults in response to various arousing stimuli as compared to less arousing stimuli (Gomez & Danuser 2004; Gomez et al. 2004; Hempel et al., 2007; Nyklicek et al. 1997; Van Diest et al. 2001). Whereas middle-aged adults showed a trend toward the same relationship between T_I and self-rated arousal as younger adults, older adults had no significant relationship between T_I change scores and self-rated arousal in this study. Recent findings have revealed age-related changes in neural recruitment during the processing of emotional information, some of which have been suggested to reflect age-related changes in attention to and appraisal of emotional contents as a consequence of goal-related motivational shifts (Nashiro et al., 2012). For instance, some studies have found that older adults show less amygdala activation than younger adults when viewing negative high-arousal pictures (Leclerc & Kensinger, 2011; Mather et al., 2004) and negative low-arousal pictures (Dolcos et al., 2014). Kehoe et al. (2013) reported age-related differences in the arousal-dependent response of several cortical regions. Yet, additional research is needed to disentangle potential age effects on the neural correlates subserving emotional valence and arousal (St. Jacques, Winecoff, & Cabeza, 2013). The activity of the respiratory network in the medulla oblongata is modulated by several cortical and subcortical brain structures (Ramirez, 2014; Subramanian & Holstege, 2014). For example, stimulation of the amygdala induced shortening of the inspiratory phase in animals (Harper, Frysinger, Trelease, & Marks, 1984) and increase in RR in humans (Masaoka & Homma, 2004). Whether the observed age-related differences in the relationship between T_I and the arousal dimension reflect shifts in emotional processing style mediated by changes in the activation of the neural substrates of emotion is a hypothesis that is worth addressing in future research endeavors.

Reports concerning changes in the thoraco-abdominal ratio during emotion in young adults have been mixed, with studies suggesting relationships with valence (Ancoli, Kamiya, & Ekman, 1980; Faulkner, 1941), arousal (Gomez & Danuser, 2004; Rehwoldt, 1911), both valence and arousal (Gomez et al., 2004; Vlemincx, Vigo, et al., 2013), or no relationships (Boiten, 1998; Gomez et al. 2005; Gomez et al. 2008). In the present study, younger adults showed the largest overall increase in abdominal breathing from baseline; yet, these changes were not related to the affective content of the series or to the self-reported affective ratings. On the contrary, older adults' increase in abdominal breathing from baseline was smallest for the unpleasant series and largest for the pleasant series, and %RC change scores increased with increasing self-rated unpleasantness. Middle-aged participants had also a significant linear increase in %RC from the pleasant to the unpleasant series, but these changes were not significantly related to their affective ratings. The difference between age groups appeared to reside primarily in the %RC response to the unpleasant contents. According to Lehrer and Woolfolk (1994), the defense response naturally tends to be accompanied by increased skeletal muscle tension in the abdomen, lower back, and perineum. Free movement of the diaphragm is met by resistance in the lower abdomen. Restricted diaphragmatic action has been found with fluoroscopic examination in individuals imaging unpleasant situations (Faulkner, 1941). We tentatively suggest that the age effect obtained for %RC reflected age-related differences in the defense response. Indirect support for this contention is provided by the affective ratings. As previously reported (Burriss et al., 2007; Grühn & Scheibe, 2008), older participants rated unpleasant contents more negatively than younger adults. Furthermore, compared to neutral contents, both middle-aged and older adults reported more negative ratings for the unpleasant series than younger adults did. The idea of enhanced defense response in older adults is supported by research showing increased startle-blink magnitude during unpleasant pictures in older adults compared with younger adults (Smith et al., 2005).

Age-related differences in baseline respiration

In addition to age-associated differences in respiratory reactivity to the picture series, age groups differed in their average baseline levels of %RC and $P_{et}CO_2$. Compared to their younger and middle-aged counterparts, older participants' breathing during the baseline periods was more thoracic. Only few studies have looked at the effect of age on the relative contribution of rib cage and abdomen to breathing. Verschakelen and Demedts (1995) did not report significant age effects on thoracoabdominal motions during quiet breathing in seated position, whereas neither Tobin et al. (1983) nor Britto et al. (2009) found significant age-related differences during quiet breathing in supine position. From young to old age, the chest wall becomes less compliant due to structural changes (Lalley, 2013), and the increased stiffening of the chest wall includes both its rib cage and diaphragm components (Estenne, Yernault, & De Troyer, 1985). The resting position of the diaphragm becomes less domed with a decrease in abdominal tone in aging (Lalley, 2013; Starr & Dalton, 2011). These factors may have contributed to make a slightly more thoracic breathing the preferred pattern among our older adults. Studies using analysis of chest wall shape and motion during breathing may provide insight on the specific changes in the thoracoabdominal pattern associated with aging (e.g., Lee, Chang, Coppieters, & Hodges, 2010).

Baseline $P_{et}CO_2$ decreased across age groups among men but not women. This finding is in accordance with a report by Anderson, Parsons, and Scuteri (1999) who found in a sample of over 300 participants that $P_{et}CO_2$ of women at rest did not change across ages, but showed a substantial decrease in men. Studies with mainly male participants also found a decrease in arterial PCO_2 with advancing age (Cardus et al., 1997; Frassetto & Sebastian, 1996). Decreases in PCO_2 as age progresses may represent an attempt to compensate for age-associated decreases in plasma pH (Frassetto & Sebastian, 1996). Concerning the reasons for the sex difference in age-associated changes in $P_{et}CO_2$, Anderson et al. (1999) suggested that the decrease in estrogen concentrations occurring after menopause might counteract the forces operating to decrease $P_{et}CO_2$ with advancing age.

Limitations and directions for future research

Future research could build on the findings of the present study and address its limitations. First, because of the cross-sectional study design, caution in interpreting results is required regarding age-related vs. cohort effects. Second, it remains to be tested whether the present results are reproduced with different types of emotion elicitation. Third, the use of longer stimuli would allow the question of age-related differences in measures of respiratory variability to be addressed, shedding light on possible modifications in stability and flexibility of respiratory regulation (Vlemincx, Abelson et al., 2013). Fourth, the variety and specificity of the selected contents may be increased. One avenue would be to explore responses to pictures depicting people of different ages, because of possible modulatory effects of the age congruence between perceiver and target persons (Wiese, Schweinberger, & Hansen, 2008). Fifth, studying breathing responses from a discrete emotions perspective as opposed to the dimensional view used here might be valuable because of accumulating evidence of differential adult lifespan trajectories in the experience of discrete emotions (Kunzmann, Kappes, & Wrosch, 2014). Sixth, this is the first study in which age effects on nine respiratory measures during affective processing were analyzed. In view of the novel nature of the present study, we deemed the exploration of these respiratory variables more important than the risk of alpha error inflation. Replication studies are warranted. Seventh, researchers may want to assess sex hormones in women, as these have been shown to influence respiration. Also, because oxygen consumption decreases as we age, it might be useful to add measures of metabolism to better interpret the respiratory findings. These measures would be valuable in particular to determine to what extent peripheral processes (e.g., muscle tension) as opposed to central processes contribute to the observed effects in ventilation and $P_{et}CO_2$. Finally, questions remain about changes in respiratory reactivity to affective challenges beyond the age of 75.

Conclusion

In conclusion, age influences responses of respiratory time parameters, $P_{et}CO_{2,}$ and thoraco-abdominal balance to affective pictures, whereas it has no significant effects on inspiratory volume and flow parameters. These findings have implications for biopsychological models of emotion and aging and for applied research fields such as respiration-based emotion regulation strategies and human-technology interaction.

Appendix

Picture numbers of the stimuli from the IAPS

Pleasant series

Appetizing food: 7200, 7270, 7330, 7470, 7480, 7488; erotic heterosexual couples: 4659, 4660, 4680, 4687, 4690, 4800; pleasant family scenes: 2299, 2311, 2332, 2360, 2530, 2598; pleasant nature: 5200, 5594, 5631, 5780, 5781, 5811; romantic heterosexual couples: 2550, 4624, 4625, 4640, 4641, 4650; sport scenes: 5621, 8080, 8180, 8186, 8400, 8490.

Unpleasant series

Environmental contamination: 9090, 9110, 9280, 9290, 9342, 9390; human loss: 2205, 2455, 2490, 2590, 9001, 9220; mutilated/burned bodies: 3010, 3030, 3068, 3071, 3110, 3150; physical violence: 2683, 3500, 3530, 6313, 6550, 6821; sick/injured human beings: 2053, 2710, 3181, 3230, 3261, 9415; suffering/dead animals: 2981, 9180, 9181, 9560, 9561, 9571.

Neutral series

Household objects: 7000, 7004, 7035, 7090, 7233, 7234; neutral human activities: 2357, 2393, 2396, 2397, 2745.1, 2850.

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This research was supported by a grant of the Opo Stiftung (Zurich, Switzerland) to Patrick Gomez and Brigitta Danuser.

We thank Miryam Cornaz, Olivier Fortini, and Bérengère Philippon for their assistance in data collection, and Aurélien Bernheim for helping with data reduction.

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Table 1 Participants' characteristics by age group

	Younger	Middle-aged	Older	All
Sample size (n)				
Men	30	23	22	75
Women	34	29	38	101
All	64	52	60	176
Age (years)	26.6 (4.6)	46.8 (4.4)	66.3 (3.9)	46.1 (17.3)
Marital status (%)				
Single	35	36	53	42
In a relationship	65	64	47	58
Employment status (%)				
Student	44	0	0	16
Working	44	75	8	41
Unemployed	12	25	2	12
Retired	0	0	90	31
Educational level (%)[a]				
Level I	0	8	13	7
Level II	25	54	50	42
Level III	75	38	37	51
Self-reported health				
Anxiety[b]	5.1 (2.2)	4.9 (2.2)	5.1 (2.3)	5.1 (2.2)
Depression[b]	1.7 (1.6)	2.2 (1.9)	2.5 (2.3)	2.1 (2.0)
Mental health[c]	71 (15)	73 (14)	77 (17)	73 (15)
Physical functioning[c]	98 (4)	95 (8)	87 (23)	94 (15)
General health perception[c]	82 (12)	82 (13)	78 (17)	80 (14)
Verbal fluency				
Animal naming task[d]	23.7 (6.3)	23.4 (6.2)	21.8 (5.8)	22.9 (6.1)
Height (cm)				
Men	180 (7)	179 (6)	175 (6)	178 (7)
Women	168 (7)	165 (7)	163 (5)	166 (7)
Weight (kg)				
Men	74 (11)	77 (12)	80 (13)	77 (12)
Women	60 (7)	60 (9)	60 (7)	60 (7)
Voluntary respiratory control (% "no")[e]	66	79	75	73

Notes for Table 1

[a] Educational level was divided into three categories: level I = no vocational training with or without practical on-the-job training; education level II: completed vocational training equivalent to apprenticeship or a degree judged equivalent; education level III: baccalaureate with or without later academic studies; values for age, self-reported health, verbal fluency, height, and weight are means with *SD*s in brackets; [b] HADS (Zigmond & Snaith, 1983), scores between 0 and 21; [c] SF-36 (Ware & Sherbourne, 1992), scores between 0 and 100 with higher scores corresponding to better health, mental health (5 items), physical functioning (10 items), general health perception (5 items); [d] (Kertesz, 1982), number of animal names in 1 minute; [e] no significant Age group effect ($\chi^2(2) = 2.75$, $p = .25$)

Table 2 Respiratory baseline means for younger, middle-aged, and older participants (*SE*s in parentheses) with *F*-values for the Age Group effect

	Younger	Middle-aged	Older	Age Group Effect
T_I (s)	1.46 (0.04)	1.55 (0.06)	1.47 (0.05)	$F(2, 173) = 0.87_a$
T_E (s)	2.59 (0.09)	2.75 (0.11)	2.73 (0.10)	$F(2, 173) = 0.74_a$
T_{TOT} (s)	4.09 (0.12)	4.34 (0.16)	4.26 (0.14)	$F(2, 173) = 0.83_a$
T_I/T_{TOT} (%)	37.2 (0.4)	37.1 (0.5)	36.3 (0.6)	$F(2, 173) = 0.88_a$
V_I (ml)	445 (15)	486 (24)	461 (23)	$F(2, 173) = 0.98_a$
V_I/T_I (ml/s)	307 (8)	320 (11)	321 (12)	$F(2, 173) = 0.59_a$
V'_E (l/min)	6.84 (0.20)	7.09 (0.28)	6.90 (0.27)	$F(2, 173) =0.26_a$
%RC (%)	41.9 (1.1)	43.6 (1.3)	49.7 (1.5)	$F(2, 173) = 10.15_{bc}, \eta_p^2 = .105$
$P_{et}CO_2$ (mmHg)				
Men	38.1 (0.5)	35.9 (0.4)	34.0 (0.6)	$F(2, 71) = 15.63_{def}, \eta_p^2 = .306$
Women	35.4 (0.4)	35.5 (0.6)	34.6 (0.6)	$F(2, 96) = 1.02_a$

Notes for Table 2

T_I: inspiratory time; T_E: expiratory time; T_{TOT}: total breath duration; T_I/T_{TOT}: inspiratory duty cycle; V_I: inspiratory volume; V_I/T_I: mean inspiratory flow; V'_E: minute ventilation; %RC: percent of rib cage contribution to V_I; $P_{et}CO_2$: end-tidal PCO_2. The age group effects did not change after including sex, voluntary respiratory control, body height, and educational level in the analyses, except for $P_{et}CO_2$. The Age Group x Sex interaction for $P_{et}CO_2$ was significant, $F(2, 167) = 4.83$, $p = .009$, $\eta_p^2 = .055$ (also after excluding 20 women using hormonal contraception and 13 women under hormonal replacement therapy). [a] $ps > .35$, $\eta_p^2 < .03$; [b] younger adults < older adults, $t(122) = 4.23$, $p < .001$, $d = 0.76$; [c] middle-aged adults < older adults, $t(110) = 3.01$, $p = .010$, $d = 0.57$; [d] younger men > middle-aged men, $t(50) = 3.11$, $p = .009$, $d = 0.88$; [e] younger men > older men, $t(49) = 5.17$, $p < .001$, $d = 1.46$; [f] middle-aged men > older men, $t(43) = 2.58$, $p = .041$, $d = 0.77$

Table 3 Mean changes and *SE*s (in parentheses) of the respiratory variables and affective ratings by age group when viewing pleasant, neutral, and unpleasant picture series

	Younger adults			Middle-aged adults			Older adults		
	Pleasant	Neutral	Unpleasant	Pleasant	Neutral	Unpleasant	Pleasant	Neutral	Unpleasant
T_I (s)	-0.03 (0.02)	-0.00 (0.04)	-0.05 (0.03)	-0.03 (0.02)	-0.03 (0.04)	-0.02 (0.03)	-0.02 (0.02)	0.02 (0.02)	0.00 (0.02)
T_E (s)	-0.26 (0.05)	-0.14 (0.10)	-0.26 (0.06)	-0.13 (0.07)	-0.14 (0.10)	-0.20 (0.08)	-0.14 (0.09)	-0.02 (0.11)	-0.11 (0.06)
T_{TOT} (s)	-0.31 (0.07)	-0.13 (0.12)	-0.34 (0.09)	-0.17 (0.09)	-0.17 (0.14)	-0.24 (0.09)	-0.17 (0.10)	-0.03 (0.12)	-0.15 (0.07)
T_I/T_{TOT} (%)	1.3 (0.3)	1.1 (0.4)	1.3 (0.3)	0.2 (0.4)	0.8 (0.5)	1.4 (0.5)	0.1 (0.5)	-0.3 (0.6)	0.9 (0.4)
V_I (ml)	-47 (11)	-41 (11)	-33 (8)	-42 (14)	-64 (19)	-49 (18)	-45 (11)	-47 (11)	-33 (11)
V_I/T_I (ml/s)	-24 (4)	-26 (5)	-19 (4)	-24 (6)	-29 (8)	-28 (8)	-29 (5)	-40 (7)	-28 (5)
V'_E (l/min)	-0.32 (0.13)	-0.44 (0.15)	-0.26 (0.13)	-0.54 (0.18)	-0.46 (0.23)	-0.34 (0.22)	-0.58 (0.14)	-0.85 (0.20)	-0.48 (0.14)
%RC (%)	-4.9 (0.6)	-5.1 (0.6)	-5.2 (0.6)	-4.1 (0.5)	-3.1 (0.6)	-3.2 (0.5)	-4.2 (0.4)	-3.8 (0.5)	-3.0 (0.4)
$P_{et}CO_2$ (mmHg)	0.3 (0.1)	0.5 (0.1)	0.2 (0.1)	0.4 (0.1)	0.5 (0.2)	0.4 (0.1)	0.9 (0.1)	1.1 (0.1)	0.7 (0.1)
Valence rating	7.3 (0.1)	5.1 (0.1)	2.7 (0.1)	7.3 (0.2)	5.5 (0.2)	2.3 (0.2)	7.6 (0.1)	5.5 (0.2)	2.0 (0.1)
Arousal rating	4.0 (0.2)	2.1 (0.1)	5.0 (0.2)	3.5 (0.2)	2.3 (0.2)	5.4 (0.3)	3.6 (0.2)	2.4 (0.2)	5.4 (0.2)

Notes for Table 3

T_I: inspiratory time; T_E: expiratory time; T_{TOT}: total breath duration; T_I/T_{TOT}: inspiratory duty cycle; V_I: inspiratory volume; V_I/T_I: mean inspiratory flow; V'_E: minute ventilation; %RC: percent of rib cage contribution to V_I; $P_{et}CO_2$: end-tidal PCO_2

Table 4 Significant polynomial contrasts across pleasant, neutral, and unpleasant picture series

	Polynom	*F* value	df	*p*	η_p^2	Pattern
T_I	quadratic	4.82	1, 169	.030	.028	inverted V-shape
T_E	quadratic	4.14	1, 170	.043	.024	inverted V-shape
T_I/T_{TOT}	linear	10.59	1, 173	.001	.058	increase
V_I/T_I	quadratic	4.25	1, 173	.041	.024	V-shape
V'_E	quadratic	4.25	1, 171	.040	.019	V-shape
%RC	linear	5.43	1, 173	.021	.030	increase
$P_{et}CO_2$	linear	4.33	1, 170	.039	.025	decrease
	quadratic	8.48	1, 170	.004	.048	inverted V-shape
Valence rating	linear	1946.31	1, 171	<.001	.919	decrease
Arousal rating	linear	105.43	1, 172	<.001	.380	increase
	quadratic	437.23	1, 172	<.001	.718	V-shape

Notes for Table 4

T_I: inspiratory time; T_E: expiratory time; T_I/T_{TOT}: inspiratory duty cycle; V_I/T_I: mean inspiratory flow; V'_E: minute ventilation; %RC: percent of rib cage contribution to V_I; $P_{et}CO_2$: end-tidal PCO_2

Table 5 Estimated models for the relationships between change scores of respiratory measures, affective ratings, and age group adjusted for sex, voluntary respiratory control, body height, and educational level

	Predictors' estimates (*SE*s)					
	Intercept	V	A	Age Group	V x Age Group	A x Age Group
T_I[a]	-0.008 (0.033) *p* = .12	-0.001 (0.002) *p* = .58	-0.005 (0.003) *p* = .066	Y: -0.025 (0.028) M: -0.017 (0.027) *p* = .66		
T_I[b]	-0.007 (0.033) *p* = .12	-0.001 (0.002) *p* = .74	0.004 (0.004) *p* = .075	Y: -0.025 (0.028) M: -0.017 (0.027) *p* = .66		Y: -0.014 (0.006) M: -0.013 (0.006) *p* = .034
T_E[a]	-0.017 (0.078) *p* = .001	0.003 (0.006) *p* = .57	-0.017 (0.007) *p* = .014	Y: -0.203 (0.074) M: -0.083 (0.078) *p* = .025*		
T_{TOT}[a]	-0.057 (0.094) *p* < .001	0.010 (0.007) *p* = .19	-0.016 (0.008) *p* = .056	Y: -0.216 (0.089) M: -0.078 (0.094) *p* = .052		
T_I/T_{TOT}[a]	0.27 (0.60) *p* = .005	-0.07 (0.04) *p* = .044	0.07 (0.04) *p* = .075	Y: 0.91 (0.52) M: 0.39 (0.50) *p* = .21		
T_I/T_{TOT}[b]	0.38 (0.59) *p* = .003	-0.02 (0.06) *p* = .015	0.18 (0.07) *p* = .13	Y: 0.91 (0.51) M: 0.39 (0.49) *p* = .20	Y: 0.07 (0.09) M: -0.27 (0.09) *p* = .001	Y: -0.10 (0.10) M: -0.26 (0.10) *p* = .044
V_I[a]	-47.67 (16.00) *p* < .001	-0.58 (0.79) *p* = .46	1.16 (0.91) *p* = .20	Y: 3.91 (13.71) M: -8.14 (13.29) *p* = .66		
V_I/T_I[a]	-33.47 (8.43) *p* < .001	0.13 (0.46) *p* = .78	1.58 (0.53) *p* = .003	Y: 11.97 (7.22) M: 3.79 (7.00) *p* = .24		
V'_E[a]	-0.66 (0.24) *p* < .001	0.00 (0.01) *p* = .98	0.04 (0.01) *p* = .002	Y: 0.34 (0.21) M: 0.13 (0.20) *p* = .26		
%RC[a]	-3.49 (0.79) *p* < .001	-0.13 (0.04) *p* = .004	0.03 (0.05) *p* = .60	Y: -1.30 (0.67) M: 0.00 (0.65) *p* = .090		
%RC[b]	-3.47 (0.79) *p* < .001	-0.26 (0.07) *p* = .009	0.02 (0.05) *p* = .74	Y: -1.32 (0.67) M: 0.00 (0.65) *p* = .083	Y: 0.29 (0.10) M: 0.13 (0.10) *p* = .016	
$P_{et}CO_2$[a]	0.85 (0.18) *p* < .001	0.01 (0.01) *p* = .13	-0.04 (0.01) *p* = .001	Y: -0.52 (0.16) M: -0.42 (0.15) *p* = .002#		

Notes for Table 5

T_I: inspiratory time; T_E: expiratory time; T_{TOT}: total breath duration; T_I/T_{TOT}: inspiratory duty cycle; V_I: inspiratory volume; V_I/T_I: mean inspiratory flow; V'_E: minute ventilation; %RC: percent of rib cage contribution to V_I; $P_{et}CO_2$: end-tidal PCO_2; V: valence rating; A: arousal rating; *SE*: standard error. [a] basic model with the main effects of the predictors V, A, and Age Group; [b] model with significant interactions. Estimates are adjusted for Sex, Voluntary Respiratory Control, Body Height, and Educational Level. Estimates for Age Group, V x Age Group, and A x Age Group are differences of the younger group (Y) and middle-aged group (M) from the older group who is the reference set to zero. The *p* values are from the Type III tests of fixed effects. [*] Younger adults < older adults ($p < .05$); [#] older adults > younger adults ($p < .01$) and older adults > middle-aged adults ($p < .05$).

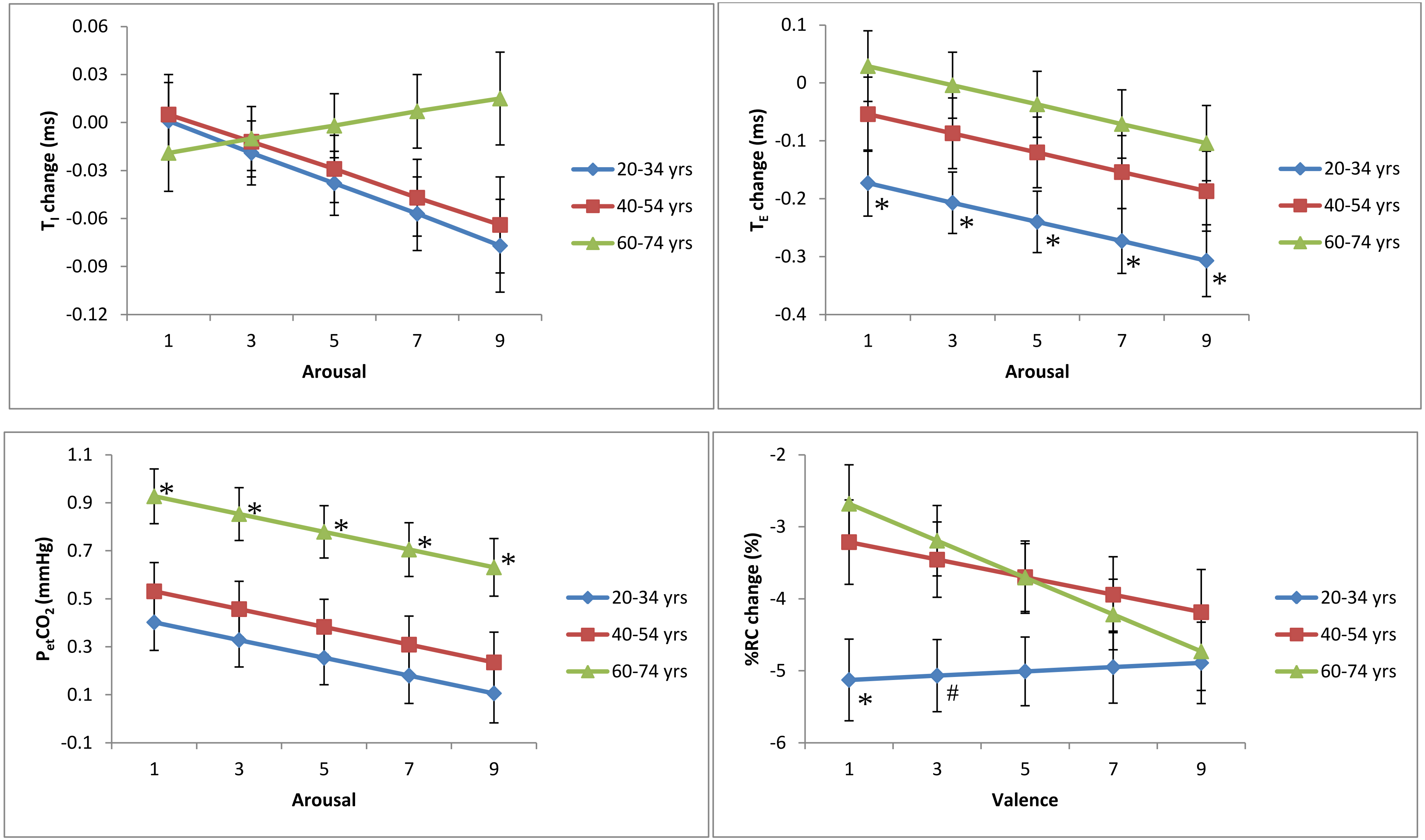
0.06
0.03
0.00
-0.03
-0.06
-0.09
-0.12
T_I change (ms)
1
3
5
7
9
Arousal
20-34 yrs
40-54 yrs
60-74 yrs
0.1
0
-0.1
-0.2
-0.3
-0.4
T_E change (ms)
*
Arousal
1.1
0.9
0.7
0.5
0.3
0.1
-0.1
P_etCO_2 (mmHg)
-2
-3
-4
-5
-6
%RC change (%)
#
Valence

Figure 1

Figure captions

Figure 1

Model-predicted estimated marginal means (*SE*s) of the relationships between the four respiratory variables inspiratory time (T_I), expiratory time (T_E), end-tidal PCO_2 ($P_{et}CO_2$), percent of rib cage contribution to V_I (%RC) and the affective ratings for the three age groups, adjusted for Sex, Voluntary Respiratory Control, Body Height, and Educational Level. X-axis: 1 represents most negative valence/lowest arousal; 9 represents most positive valence/highest arousal. Upper right (T_E): * younger adults < older adults at the same arousal levels ($p < .05$); lower left ($P_{et}CO_2$): * older adults > younger and middle-aged adults at the same arousal levels ($p < .05$); lower right (%RC): * younger adults < middle-aged and older adults at the same valence level ($p < .05$), # younger adults < older adults at the same valence level ($p < .05$) (see Table 5 for predictors' estimates).