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BRIEF REPORT

Sigh rate and respiratory variability during mental load and sustained attention

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Abstract

Spontaneous breathing consists of substantial correlated variability: Parameters characterizing a breath are correlated with parameters characterizing previous and future breaths. On the basis of dynamic system theory, negative emotion states are predicted to reduce correlated variability whereas sustained attention is expected to reduce total respiratory variability. Both are predicted to evoke sighing. To test this, respiratory variability and sighing were assessed during a baseline, stressful mental arithmetic task, nonstressful sustained attention task, and recovery in between tasks. For respiration rate (excluding sighs), reduced total variability was found during the attention task, whereas correlated variation was reduced during mental load. Sigh rate increased during mental load and during recovery from the attention task. It is concluded that mental load and task-related attention show specific patterns in respiratory variability and sigh rate.

Descriptors: Mental arithmetic, Sustained attention, Sighing, Respiratory variability

In contrast with the extensive literature on the effects of attention and emotion on cardiovascular variability and basic respiratory parameters, little is known about the effect on respiratory variability, and the few existing studies show inconsistent results. Spontaneous breathing during rest in healthy subjects shows considerable variability (Donaldson, 1992; Hughson, Yamamoto, & Fortrat, 1995; Small, Judd, Lowe, & Stick, 1999; Tobin, Yang, Jubran, & Lodato, 1995; Wysocki, Fiamma, Straus, Poon, & Similowski, 2006), and some findings suggest a reduction during anxiety and negative affect (Van Diest, Thayer, Vandeputte, Van de Woestijne, & Van den Bergh, 2006). Increased respiratory variability is characteristic of both positive affective states such as fun and amusement (Boiten, 1998) and negative emotional states, such as anger, resentment, guilt, and sorrow (Stevenson & Ripley, 1952), pain (Boiten, 1998), and panic disorder (Abelson, Weg, Nesse, & Curtis, 2001; Martinez et al., 2001; Wilhelm, Trabert, & Roth, 2001; Yeragani, Radhakrishna, Tancer, & Uhde, 2002).

To integrate these conflicting findings, we previously proposed to distinguish between various types of variability: correlated and random (Vlemincx, Van Diest, Lehrer, Aubert, & Van den Bergh, 2010). From a dynamic systems perspective, healthy breathing is characterized by considerable correlated respiratory variability representing homeostatic capacity and respiratory stability and some random variability enhancing respiratory sensitivity and adaptability (Bruce & Daubenspeck, 1995). The inconsistent findings above mostly relied on general measures of total variability, which can be interpreted as the sum of random and correlated variability. Increases in total variability during emotional states could be due to excessive random variability, indicating a lack of stability. In contrast, decreases in total respiratory variability could be the result of a lack of correlated variability, ensuing from sustained psychological processes supporting task-related attention or behavior inhibiting responsiveness to environmental changes (Thayer & Lane, 2000).

A related aspect of respiratory variability that has largely been disregarded is sighing. We have previously theorized that sighing acts as a resetter of the respiratory system to restore healthy variability either when respiration progressively lacks variability or when respiratory variability becomes excessively random (Vlemincx, Van Diest, et al., 2010).

In the present study sighing and random and correlated respiratory variability were assessed during a stressful mental load task, predicted to induce random variability and sighing, and a nonstressful attention task, predicted to reduce total variability, after which sighing will occur.

Methods

Participants

Forty-three healthy students participated in the study (21 men, age 18–22 years). The experiment was approved by the Ethics

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Committees of the Department of Psychology and of the Faculty of Medical Sciences.

Apparatus

Breathing data were measured continuously by means of respiratory plethysmography using the LifeShirt System (Vivometrics, Inc., Ventura, CA). Motion and posture were assessed by the LifeShirt accelerometers. Electrocardiogram, end-tidal pCO_2 and electromyography data are discussed elsewhere (Vlemincx, Taelman, Van Diest, & Van den Bergh, 2010).

Procedure

Upon arrival, participants were informed about the course of the experiment, signed an informed consent form, and were presented with the written instructions. Participants were informed that the experiment consisted of different tasks. The first task was to watch the documentary *The March of the Penguins* during baseline. The film was also watched during recovery after each of the other tasks. They were ensured that no questions about the movie would be asked later on and they could relax and enjoy watching the film. The second task was a mental arithmetic task performed under stressor conditions. A continuous series of sums of five operations with a two- or three-digit number had to be performed without any verbalization (e.g., $361+7 \div 24 \times 2+13$). Participants were instructed not to speak, mumble, or move their lips. Using the mouse cursor, they indicated the correct answer by choosing between three alternatives, after which feedback was given. The five participants who achieved the most correct answers were rewarded with a movie ticket. The experimenter was seated next to the participant. Mental arithmetic is widely used to induce stress, as it affects several physiological indices of stress (Kelsey et al., 1999; Willemsen, Ring, McKeever, & Carroll, 2000). Moreover, specific task characteristics increase the stress level: high task difficulty, feedback, speed- and accuracy-related evaluation and rewards, and near observation (Boiten, Frijda, & Wientjes, 1994; Gaillard & Wientjes, 1994; Kelsey et al., 2000). The third task was a nonstressful but attention engaging task during which participants were presented with three different numbers from which they had to indicate the largest number using the mouse cursor. Compared to the mental arithmetic task, this attention task required the same motor movement as well as sustained task attention, but task difficulty was extremely low, no time constraints were applied, and no performance rewards were given. Before the experiment started, participants were connected to the LifeShirt System, explicitly instructed again not to speak, to sit comfortably, not to change posture, and not to move except for their dominant hand using the mouse cursor.

In summary, the experiment consisted of a series of seven 6-min phases, starting with a baseline, which was followed by three 6-min tasks, each followed by a 6-min recovery period (RC). The three tasks were a nonstressful attention task (AT) and two mental arithmetic tasks (MT1 and MT2), presented in completely randomized order. Randomization was controlled by custom-made stimulus presentation and data acquisition software Affect 4.0 (Spruyt, Clarysse, Vansteenwegen, Baeyens, & Hermans, 2010).

Data Analysis

Respiratory measures. Respiratory waveforms were edited using dedicated Vivologic software (Vivometrics, Inc., Ventura, CA; for more details, see Vlemincx, Van Diest, et al., 2010). Because of unreliable data acquisition, data from 1 participant were excluded from analysis. Movement artifacts were controlled for by evaluating the accelerometer signals: All participants maintained the same posture during the whole experiment, mean motion value was 0.5 (range 0–3) on a scale from 0 (*no movement at all*) to 5 (*resting*) to 15 (*walking*) to 50 (*running fast*).

Next, respiratory parameters were calculated breath by breath. Mean basic respiratory parameters—inspiratory volume (Vi), respiration rate (RR = 60/total breath time), minute ventilation (MV = RR $\times$ Vi), and contribution of ribcage breathing to inspiratory volume (%RCi)—respiratory variability, and the number of sighs were calculated within each 6-min phase. Sighs within each phase were defined as breaths with an inspiratory volume at least 2 times as large as the mean inspiratory volume during this phase. The coefficient of variation (CV) and autocorrelation (the correlation of a signal with itself) at one breath lag (AR) of Vi, RR, and MV were calculated as measures of total respiratory variability and correlated respiratory variability, respectively (Tobin et al., 1995). Both measures of respiratory variability were calculated including and excluding sighs.

Statistical analysis. Respiratory measures were subjected to a repeated measures analysis (ANOVA) with phase (baseline, AT, MT1, MT2, RC after AT, RC after MT) as a within-subject variable. To explore further differences between tasks, baseline, and RC, post hoc contrasts were tested by means of Tukey comparisons. Reported p values are Greenhouse–Geisser corrected and ε values are reported. Effect sizes are reported as η_p^2.

Results

The effect of phase was significant for all respiratory measures (see Table 1). The following post hoc comparisons were significant at $\alpha = .01$.

Basic Respiratory Parameters

Significantly higher Vi during baseline and MT1 was found compared to AT ($p < .0001$) and RC after MT ($p < .001$). Increased RR seemed characteristic of both AT and MT: RR during AT, MT1, and MT2 was significantly higher compared to baseline ($p < .0001$) and RC periods ($p < .0001$). MV during baseline and AT was significantly lower than MV during MT1 ($p < .0001$), but was significantly higher than MV during RC phases ($p < .001$). %RCi during MT1 did not differ from %RCi during baseline and MT2 and was significantly higher compared to AT ($p < .001$) and RC periods ($p < .001$), suggesting that increased %RCi was specific of MT.

Respiratory Variability

Compared to baseline, CV(Vi) was significantly higher during MT1 ($p < .0001$), MT2 ($p < .0001$), and RC after AT ($p < .0001$), but did not differ from CV(Vi) during AT and RC after MT. Excluding sighs reduced overall CV(Vi), but did not change this pattern across phases. In line with the predicted results, total variation in Vi was increased during MT. Whereas correlated variability was predicted to be reduced during MT, AR(Vi) appeared to be significantly lower during MT2, but not during MT1. Compared to baseline, AR(Vi) was significantly lower during MT2 ($p < .0001$) and RC after AT ($p < .001$). After excluding sighs, AR(Vi) during baseline and during RC after AT did no longer differ.

CV(RR) during AT was significantly lower compared to MT1 ($p < .0001$), MT2 ($p < .001$), and RC after AT ($p < .001$). When sighs were excluded, CV(RR) during AT became significantly lower compared to baseline ($p = .01$). Thus, as predicted, AT was

Table 1. *Mean (SD) Basic Respiratory Parameters—Vi (ml), RR (Breaths/Min), MV (l/Min), RCi (%)—Sigh Rate (N), and Variability Measures (CV and AR) Including and Excluding Sighs during the Experimental Phases*

				Phase					
	$F(5,205)$	ε	η_p^2	Baseline	AT	MT1	MT2	RC after AT	RC after MT
Mean									
Vi	9.31***	.60	.19	375.48 $_a$ (168.57)	334.33 $_b$ (147.97)	375.31 $_a$ (163.93)	353.32 $_{a,b}$ (153.22)	351.47 $_{a,b}$ (154.93)	343.31 $_b$ (153.96)
RR	31.99***	0	.44	16.18 $_a$ (3.27)	18.76 $_c$ (3.16)	18.19 $_{b,c}$ (3.35)	17.41 $_b$ (3.25)	15.88 $_a$ (2.41)	15.92 $_a$ (2.93)
MV	30.51***	.49	.43	5.78 $_a$ (2.17)	6.00 $_a$ (2.28)	6.47 $_c$ (2.71)	5.8 $_a$ (2.38)	5.34 $_b$ (2.16)	5.22 $_b$ (2.10)
RCi	7.33***	.70	.15	40.85 $_{a,b}$ (7.23)	39.14 $_b$ (8.18)	42.95 $_a$ (8.88)	41.66 $_{a,b}$ (8.46)	39.02 $_b$ (7.00)	38.88 $_b$ (7.57)
Sigh rate	6.41***	.71	.14	0.79 $_a$ (1.35)	1.38 $_{a,b}$ (1.34)	1.93 $_b$ (2.10)	2.05 $_b$ (1.94)	2.12 $_b$ (1.89)	1.36 $_{a,b}$ (1.33)
CV									
Vi	11.37***	.76	.22	24.00 $_a$ (13.63)	29.56 $_{a,b}$ (12.19)	36.35 $_{b,c}$ (16.30)	38.29 $_c$ (17.60)	36.61 $_{b,c}$ (15.69)	30.5 $_{a,b}$ (13.64)
Vi ex. sighs	9.07***	.67	.18	18.54 $_a$ (6.63)	20.01 $_{a,b}$ (6.25)	24.28 $_c$ (7.09)	23.35 $_c$ (7.96)	21.98 $_{b,c}$ (7.08)	21.41 $_{a,b,c}$ (7.69)
RR	5.93***	.81	.13	16.37 $_{a,b}$ (7.16)	13.34 $_a$ (4.50)	18.40 $_b$ (8.39)	18.24 $_b$ (8.14)	17.84 $_b$ (6.75)	16.43 $_{a,b}$ (6.59)
RR ex. sighs	5.22***	.80	.11	15.95 $_{a,b}$ (7.10)	12.40 $_a$ (4.39)	17.28 $_b$ (8.44)	16.86 $_b$ (8.23)	16.54 $_b$ (6.75)	15.62 $_{a,b}$ (6.28)
MV	5.76***	.67	.12	20.59 $_a$ (8.14)	21.17 $_{a,b}$ (5.83)	25.80 $_{b,c}$ (8.21)	25.52 $_{a,b,c}$ (9.32)	26.52 $_c$ (11.88)	23.49 $_{a,b,c}$ (8.41)
MV ex. sighs	5.86***	.74	.13	19.13 $_a$ (6.19)	19.4 $_{a,b}$ (5.30)	23.72 $_c$ (6.97)	22.28 $_{a,b,c}$ (7.95)	23.13 $_{b,c}$ (8.79)	21.39 $_{a,b,c}$ (6.77)
AR									
Vi	8.81***	.65	.18	.20 $_a$ (.18)	.12 $_{a,b}$ (.20)	.11 $_{a,b,c}$ (.23)	.01 $_c$ (.13)	.05 $_{b,c}$ (.13)	.14 $_{a,b}$ (.13)
Vi ex. sighs	4.6**	.79	.10	.24 $_a$ (.18)	.24 $_a$ (.19)	.22 $_a$ (.19)	.11 $_b$ (.15)	.18 $_{a,b}$ (.17)	.21 $_{a,b}$ (.14)
RR	6.03***	.82	.13	.26 $_a$ (.20)	.22 $_{a,b}$ (.17)	.12 $_b$ (.15)	.13 $_b$ (.13)	.21 $_{a,b}$ (.18)	.22 $_{a,b}$ (.15)
RR ex. sighs	6.04**	.82	.13	.47 $_a$ (.11)	.46 $_{a,b}$ (.10)	.40 $_{b,c}$ (.08)	.39 $_c$ (.06)	.44 $_{a,b,c}$ (.10)	.46 $_{a,b}$ (.09)
MV	8.4***	.75	.17	.28 $_{a,b}$ (.18)	.25 $_{a,b}$ (.21)	.30 $_b$ (.24)	.11 $_c$ (.16)	.18 $_{a,c}$ (.16)	.23 $_{a,b}$ (.14)
MV ex. sighs	7.66***	.76	.16	.31 $_{a,b}$ (.18)	.32 $_{a,b}$ (.21)	.37 $_b$ (.23)	.18 $_c$ (.18)	.23 $_{a,c}$ (.17)	.26 $_{a,b,c}$ (.14)

Note: Vi: inspiratory volume, RR: respiration rate, MV: minute ventilation, RCi: portion ribcage breathing, CV: coefficient of variation, AR: autocorrelation, AT: attention task, MT: mental arithmetic task, RC: recovery.
**$p < .001$,
***$p < .0001$; means with different subscripts are statistically different at $\alpha = .01$ using Tukey-corrected p values.

marked by decreased total variability in RR. AR(RR) during baseline was significantly higher compared to MT1 ($p < .001$) and MT2 ($p < .01$), but did not differ from all other phases, suggesting that, in line with the hypotheses, correlated variability in RR was reduced during MT. Excluding sighs yielded the same pattern.

CV(MV) was significantly lower during baseline, compared to MT1 ($p < .01$) and RC after AT ($p < .001$), but did not differ from CV(MV) during AT, MT2, and RC after MT. Thus, as hypothesized, total variability in MV increased during MT. However, consistent with variability in Vi, correlated variability in MV was decreased during MT2 but not during MT1: Higher AR(MV) was found during baseline and AT compared to MT2 ($p < .0001$). AR(MV) during MT1 appeared to be significantly higher compared to MT2 ($p < .0001$) and RC after AT ($p < .01$). Excluding sighs yielded the same results.

Sighing

Sigh frequency was significantly higher during MT1 ($p < .01$), MT2 ($p < .001$), and RC after AT ($p < .0001$) compared to baseline. Sigh frequency during baseline did not differ from that during AT and RC after MT. This suggests that, consistent with our predictions, sighs appeared characteristic of MT and RC following AT.

DISCUSSION

The aim of the present study was to investigate respiratory variability and sigh frequency during a stressful mental arithmetic task and a nonstressful attention task. Increased sighing was found during mental load, which was characterized by increased random breathing, and following task-related attention, which was characterized by a reduction of respiratory variability.

Basic respiratory measures in this study showed rapid shallow breathing during sustained task attention, whereas more thoracic, faster, and (during the first task) deeper breathing was found during mental arithmetic. The latter matches breathing responses during high-arousal negative affective states (Boiten et al., 1994), suggesting that mental stress was successfully induced by mental arithmetic.

In addition, the mental load task and the attention task showed different patterns in respiratory variability measures. The attention task reduced total respiratory variability (of respiration rate excluding sighs) compared to baseline. During the mental load task, total breathing variability increased, but autocorrelation was reduced, which implies increased random respiratory variability. Together, these findings suggest that stressors might increase random variability, whereas sustained attention states might reduce total variability.

As predicted, sigh rate strongly increased during the mental arithmetic task and following the attention task. Both findings fit the hypothesis that sighing acts as a psychophysiological resetter (Vlemincx, Van Diest, et al., 2010); sighing may (temporarily) reset physiological changes that characterize psychological states. On the one hand, negative emotional states elicit increasing tension, and, accordingly, breathing may become progressively random, which may be counteracted by sighing. Recent evidence shows that sighs occur toward increasingly random breathing and reset structured correlated respiratory variability (Baldwin et al., 2004; Vlemincx, Van Diest, et al., 2010). The result that sigh rate increases during the mental load task, which was characterized by decreased autocorrelation and more random breathing, fits this finding.

On the other hand, sighing might also reset respiratory variability as it becomes reduced during sustained attention. A lack of respiratory variability elicits atelectasis, the progressive collapse of alveoli, which in turn causes a decrease in lung compliance and gas exchange efficiency. These physiological consequences are restored by sighing (Bendixen, Smith, & Mead, 1964; Caro, Butler, & Dubois, 1960; Cherniack, Euler, Glowgowska, & Homma, 1981;

Ferris & Pollard, 1960; McIlroy, Butler, & Finley, 1962; Mead & Collier, 1959; Reynolds, 1962). This suggests that participants recovered from reduced respiratory variability and its associated physiological consequences with sighing at the end of the attention task.

It is likely that across the life span of a person, an intricate relationship develops between the physiological and psychological consequences of sighing, such that persons learn to use sighing as a coping response with aversive states to induce subjective relief and beneficial physiological effects. In line with this, increased sigh rates are found during relief of dyspnea and perceived restlessness (Hirose, 2000), relief of negative affectivity and craving (McClernon, Westman, & Rose, 2004), and relief of stress (Soltysik & Jelen, 2005; Vlemincx et al., 2009).

In this study, correlated variability quantified by autocorrelation at one breath lag holds only one level of correlated variability and therefore reflects only a fraction of all variability of a correlated nature. Therefore, the interpretation of our results is limited to one component of correlated variability as quantified by autocorrelation at one breath lag.

The present study shows that it is important to consider measures of respiratory variability and sighing in addition to mean basic respiratory parameters when investigating the influence of emotion upon respiration.

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