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# Cardiorespiratory Assessment of Mental Load in Pilot Selection

**Mariel Grassmann**

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Supervisor: Prof. Dr. Omer Van den Bergh

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ASSOCIATIE KU LEUVEN

# Summary

The ability to cope with mentally demanding situations and maintain cognitive functioning is a core requirement for airline pilots. Stress resistance is therefore an important selection criterion which is, however, difficult to assess. The main objective of this project was to enhance the assessment of stress resistance in pilot selection and to investigate the relationship between mental load and respiration as well as cardiac parameters.

At the German Aerospace Center, the evaluation of stress resistance is currently based on observer ratings of visible strain symptoms and self-reports as well as performance measures. Since mental load has been shown to have clear effects on physiological systems, we investigated whether cardiorespiratory measures that can be obtained cheap and unobtrusively provide additional valuable information. While cardiac parameters have been studied extensively in response to mental load, little research has been devoted to the usefulness of respiratory measures – even though respiration is closely related to psychological processes under stress. Existing studies revealed that, on the one hand, respiratory reactivity might reflect mental load and, on the other hand, inappropriate changes might even cause performance decrements. However, further empirical evidence is needed to establish both findings.

In a review study we integrated empirical findings on respiratory changes from baseline to mentally demanding task periods and possible effects of task difficulty and task duration. Based on the available studies, we found that mentally demanding episodes were characterized by faster breathing and higher minute ventilation, but that the respiratory amplitude was generally invariant to mental load. While total variability in respiratory rate was not systematically affected by mental load, we found that correlated variability was reduced. In addition, our analyses revealed that mental load may lead to overbreathing (decreased end-tidal carbon dioxide levels) and to higher oxygen consumption and carbon dioxide production. Habituation effects were only reported for respiratory rate. Overall, this review showed that several respiratory measures are sensitive to mental load. Since most of the available studies were restricted to traditional time and volume parameters, we conducted an experimental study which also included variability and gas exchanges measures.

The present experimental study was conducted on a sample of pilot candidates and aimed at investigating whether cardiorespiratory measures are sensitive to mental load as induced by a highly demanding multiple task that resembles the mental requirements of pilot selection and routine flight in a simplified way. We assessed heart rate, heart rate variability, respiratory rate, respiratory variability, and partial pressure of end-tidal carbon dioxide during baseline, task, and recovery periods. All measures changed clearly from baseline to task. Effects of recovery were observed for all measures besides end-tidal carbon dioxide. When analyzing associations with cognitive performance, small effects were found for respiratory measures, indicating that a more flexible system is related to higher cognitive performance. In addition, we investigated individual differences in personality and their associations with cardiorespiratory activation. While a lower cardiac reactivity was found in participants characterized by cognitive avoidant coping, respiratory rate was reduced in participants with higher levels of self-focused attention. Negative affectivity was not associated with cardiorespiratory activation but moderated the relationship of cardiac and self-reported arousal measures. Given that physiological and self-report measures of mental load are often combined when evaluating operator load, our results imply that an integration of individual differences may reduce unexplained variance. Taken together, the present experimental findings suggest that respiratory parameters would be a useful supplement to the current measures being used to assess stress resistance in pilot selection and that a consideration of trait characteristics may increase the validity of workload assessments.

# Samenvatting

Een kernvereiste voor luchtvaartpiloten is de vaardigheid om om te gaan met mentaal veeleisende situaties zonder verlies aan cognitief functioneren. Daarom is stressbestendigheid een belangrijk selectiecriterium. Stressbestendigheid is echter moeilijk te beoordelen. Het belangrijkste doel van dit project was het verbeteren van de evaluatie van stressbestendigheid bij selectie van piloten en het onderzoeken van de relatie tussen mentale belasting en ademhalings- en hartritmeparameters.

In het German Aerospace Center gebeurt de evaluatie van stressbestendigheid op dit moment op basis van beoordelaars die zichtbare symptomen van spanning observeren, zelfrapportage en performantiematen. Omdat mentale belasting duidelijke effecten heeft op verschillende fysiologische systemen, hebben we onderzocht of cardiorespiratoire metingen die goedkoop en niet-invasief zijn, kunnen bijdragen tot bijkomende informatie. Hoewel hartritmeparameters als reactie op mentale belasting uitgebreid bestudeerd werden, werd slechts weinig onderzoek gewijd aan de bruikbaarheid van ademhalingsparameters, desondanks de vaststelling dat ademhalingsparameters zeer sterk geassocieerd zijn met psychologische processen tijdens stress. Bestaande studies tonen aan dat enerzijds mentale belasting leidt tot een specifieke respiratoire reactiviteit, en anderzijds, ongepaste veranderingen in de ademhaling kunnen leiden tot een verminderde performantie. Verdere empirische evidentie is nodig om beide bevindingen verder aan te tonen.

In een review studie, integreerden we empirische bevindingen betreffende ademhalingsveranderingen tijdens een basislijn en mentaal belastende taken, en potentiële effecten van taakmoeilijkheid en taakduur. Op basis van de beschikbare studies, vonden we dat mentaal belastende taken gekarakteriseerd werden door een snellere ademhaling en een hoger minuutventilatie, maar dat de diepte van de ademhaling niet afhankelijk was van mentale belasting. Totale variabiliteit in ademfrequentie werd niet systematisch beïnvloed door mentale belasting, maar gecorreleerde variabiliteit tijdens mentale belasting was verlaagd. Onze analyses tonen ook aan dat mentale belasting kan leiden tot hyperventilatie (verlaagde koolzuurspanning), meer zuurstofverbruik en koolzuurproductie. Habituatie-effecten werden enkel gerapporteerd voor ademfrequentie. Algemeen toonde deze review aan dat verschillende ademhalingsparameters gevoelig zijn voor mentale belasting. De meeste studies beperkten zich tot traditionele tijd- en volumeparameters. Daarom voerden we een experimentele studie uit die maten van variabiliteit en gasuitwisseling bestudeerde.

De huidige experimentele studie werd uitgevoerd op een steekproef van kandidaat-piloten. Het doel van deze studie was te onderzoeken of cardiorespiratoire maten gevoelig zijn voor mentale belasting, geïnduceerd door middel van een zeer veeleisende meervoudige taak die, in vereenvoudigde vorm, overeenkomt met de mentale vereisten voor selectie van piloten en routinevluchten. We maten hartritme, hartritmevariabiliteit, ademfrequentie, ademvariabiliteit en koolzuurspanning tijdens een basislijn, de taak en herstelperiodes. Alle maten verschilden duidelijk tussen basislijn en taak. Effecten van herstel waren aanwezig voor alle maten behalve koolzuurspanning. Na analyse van de associaties met cognitieve performantie, werden kleine effecten gevonden voor ademhalingsparameters die aantoonden dat een meer flexibel systeem geassocieerd is met een betere cognitieve performantie. We onderzochten ook individuele verschillen in persoonlijkheid en hun relatie met cardiorespiratoire activatie. Een lagere hartritmereactiviteit werd gevonden bij deelnemers met cognitief vermijdende coping. Een lagere ademfrequentie werd gevonden bij deelnemers met hogere zelfgerichte aandacht. Negatieve affectiviteit was niet geassocieerd met cardiorespiratoire activiteit, maar beïnvloedde de relatie tussen hartritmeparameters en zelfrapporteringen van arousal. Gegeven dat fysiologische maten en zelfrapporteringsmaten van mentale belasting vaak gecombineerd worden bij de evaluatie van werkbelasting, suggereren onze resultaten dat een integratie met beoordeling van individuele

verschillen de onverklaarde variantie kan verminderen. Samengevat, de huidige experimentele bevindingen suggereren dat ademhalingsparameters een bruikbare toevoeging zijn aan de maten die op dit moment gebruikt worden om stressbestendigheid bij selectie van piloten te beoordelen, en dat de toevoeging van persoonlijkheidskarakteristieken de validiteit van beoordelingen van werkbelasting kan verhogen.

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CONTENTS

1. General introduction ..... 1

2. Theoretical and empirical background ..... 3

    2.1. The concept of mental load ..... 3

    2.2. Measuring mental load ..... 6

    2.3. Interindividual differences ..... 12

3. Research questions ..... 15

4. Respiratory changes in response to mental load: A systematic review ..... 17

    4.1. Abstract ..... 17

    4.2. Introduction ..... 17

    4.3. Literature research and study selection ..... 22

    4.4. Data extraction and synthesis ..... 23

    4.5. Discussion ..... 30

5. The role of respiratory measures to assess mental load in pilot selection ..... 39

    5.1. Abstract ..... 39

    5.2. Introduction ..... 39

    5.3. Methods ..... 44

    5.4. Results ..... 49

    5.5. Discussion ..... 52

6. Individual differences in cardiorespiratory measures of mental workload ..... 56

    6.1. Abstract ..... 56

    6.2. Introduction ..... 56

    6.3. Methods ..... 61

    6.4. Results ..... 67

    6.5. Discussion ..... 72

7. General discussion ........ 77

7.1. Respiration in the measurement of mental load ........ 77

7.2. Implications for pilot selection ........ 81

References ........ 85

Appendix ........ 107

# 1 General introduction

Routine airline flight typically involves different types of cognitive demands. During take-off, landing, and uncommon situations such as sudden changes in weather conditions, pilots have to accomplish several tasks in parallel as, for instance, monitoring flight status and systems, following flight deck checklists, and communicating with air traffic control. While these periods require high levels of concentration and mental activity, pilots have to remain vigilant in smooth flight conditions of cruise flight which is controlled by automated systems and requires only little task-related activation. The most demanding situations are sudden and unexpected flight incidents and emergency maneuvers which are not only characterized by very high information load but also by emotional stress due to the pilots' responsibility for passengers and aircraft safety. In such a situation, the pilot is required to stay calm and concentrated and to quickly shift from low to high task-related activation. As a consequence, basic cognitive skills such as spatial orientation, high information processing capacity, mental flexibility to quickly adapt to different requirements, and the ability to remain focused in taxing conditions (in aviation referred to as "stress resistance") are among the most important job demands for pilots. Also social skills such as teamwork, leadership, and adherence to procedures are important requirements which may, however, be impaired during critical situations if the operator is too vulnerable to stress.

The research of the present thesis was conducted in parallel with my employment at the Department of Aviation and Space Psychology of the German Aerospace Center (DLR, Deutsches Zentrum für Luft- und Raumfahrt) which is located in Hamburg. The psychological department is primarily responsible for the selection of civilian and military pilots, air traffic controllers, and astronauts, but also involved in training and counseling. Despite the increasing level of automation and computer assistance, the human operator has still a predominant role in aviation – a field which is characterized by highly specialized processes and technology and very low error tolerance.

The basic motivation for this project was to investigate the assessment of stress resistance and to further improve the current pilot selection processes at DLR. The entire selection procedure comprises two stages: a one-day computer-based assessment of basic cognitive skills and abilities (stage 1) and a two-day testing procedure for the assessment of personality and social aspects in mentally demanding situations (stage 2). Behavior and performance are evaluated during exercises on information processing and conflict management in single and group settings, as well as during exercises in a flight simulator. Since all of these tasks are complex and unfamiliar to the applicants, they are considered to be highly demanding. The assessment of stress resistance is currently based on performance measures on the one hand and observer and self-ratings on the other hand. Specifically, examiners continuously register visible strain symptoms such as trembling voice or physical tension to obtain information on stress resistance, but validity of these observations is unclear. Self-ratings are another common selection tool. However, they are prone to social desirability and memory lapse. The purpose of this project is to investigate whether the inclusion of cardiorespiratory measures during task performance may advance the assessment of stress resistance in pilot selection.

The data presented in this thesis are based on a systematic review on mental load and respiration and an experimental study which was run to investigate two aspects: the usefulness of cardiorespiratory measures and the role of individual differences for monitoring mental load. For practical reasons, the review and experimental analyses were conducted in parallel. The experimental study was thus not intended to address the research gaps revealed by the review, but rather to investigate cardiorespiratory correlates of mental load in pilot selection. As the review, however, covers a broader research question than the experimental part, findings of the review study (Chapter 4) will precede the experimental work (Chapter 5 and 6).

# 2 Theoretical and empirical background

Whereas regular cruise flight is characterized by low operator load and even boredom, take-off and landing involve intense concentration and mental activity to manage the associated workload. Critical incidents such as system breakdown and engine failure require accurate decisions within a few seconds. Such situations lead to peak levels of mental load, but are in some individuals also accompanied by emotional stress. Both mental load and stress may impair situational awareness and lead to performance decrements (Endsley, 1999). As indicated by accident reports (e.g., Carley, 1999), extreme levels of mental load and stress can also induce hyperventilation, which is associated with reduced cerebral blood flow and deficient cognitive performance (Van Diest, Stegen, Van de Woestijne, Schippers, & Van den Bergh, 2000). Even though incidents happen rarely, operators have to be capable of restoring the situation. Apart from basic flying skills, extensive training, and experience, the ability to cope with stressful situations and to stay in control is decisive and therefore an important criterion for pilot selection (Goeters, Maschke, & Eißfeldt, 2004).

While research on the psychophysiology of negative emotions and stress is particularly relevant for pilot training and accident investigation, a better understanding of physiological and behavioral correlates of mental load is central to diagnostics within pilot selection.[1] In the following, we will introduce the concept of mental load, the existing measurement techniques, and the role of interindividual differences.

### *The concept of mental load*

Mental load (or mental workload) results from an aggregation of various aspects that are important in the context of pilot selection. Considering the multifaceted nature of this concept, mental load has been defined as the “difference between the capacities of the information processing system that are required for task performance to satisfy performance expectations and the capacity available at any given time” (Gopher &

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[1] Investigating whether physiological measures also prove useful to evaluate emotional resilience in critical flight situations is beyond the scope of this project.

Donchin, 1986, p. 41-3) or, likewise, as the ratio between task demands and operator capacity (e.g., Kantowitz, 1987; O'Donnell & Eggemeier, 1986). Since resources of the human processing system are limited, the level of mental load depends on the interaction of task difficulty and complexity on the one hand and skills, abilities, and motivational processes of the operator on the other hand. For experimental research, mental load is usually implemented by using cognitive tasks. According to Carroll, a cognitive task is "any task in which correct or appropriate processing of mental information is critical to successful performance" (Carroll, 1993, p. 10).

Importantly, the concept of mental load has to be differentiated from the concept of stress. Due to their close relationship, the two terms are often confused or incorrectly used. As outlined above, also in pilot selection the term "stress resistance" is used to describe the ability to stay focused under mentally demanding conditions. A common definition of stress has been provided by Lazarus and Folkman (1984, p. 19): "Psychological stress is a particular relationship between the person and the environment that is appraised by the person as taxing or exceeding his or her resources and endangering his or her well-being". In line with many other definitions, stress is related to discomfort caused by the appraisal that external demands are going beyond one's own coping abilities. In human factors and ergonomics, the term stress (or stressor) is usually defined as the external event that disrupts normal functioning, while the resulting state of the individual is referred to as strain (e.g., Salvendy, 2005).

A comparison of mental load and stress shows that both concepts have a distinct theoretical background but share two elements: First, there is a discrepancy between external demands and internal resources, and second, this discrepancy leads to some kind of energy mobilization. Principle differences are that the energy mobilized under mental load is task-related, activates mental processes, and enhances concentration in order to "satisfy performance expectations" (see above). Energy mobilization under stress, however, is triggered by negative emotions and aims at protecting core aspects of the self against environmental demands such as socio-evaluative threats, which may impair mental processes and task concentration (Gaillard, 1993; Gaillard & Wientjes, 1994). This basic distinction of energetic processes entails further differences between the two concepts concerning emotional, attentional, and behavioral processes (Gaillard, 1993). While mental load is mostly accompanied by positive affect and feelings of challenge and motivation, stress induces negative affect and feelings of threat, depression, or frustration. Another important difference refers to the focus of attention. Under mental load, attention is focused on the execution of the task to monitor performance, whereas under stress, attention is turned to threats related to the self. As a consequence, the behavioral response to mental load is mainly driven by task requirements in order to successfully accomplish the task. Under stress, however, the individual acts to protect the self what may result in anxiety, aggressive behavior, or withdrawal. Specific behavioral processes might further encompass differences in anticipation of as well as in recovery from the situation. When anticipating stressful situations, the organism tends to overreact, and hyperaroused states often sustain for a longer period of time after the exposure to stress has ended. In comparison to stress, mental load is characterized by lower reactivity levels before the task and more often by feelings of fatigue than by overreactivity after the task (see also Brosschot, Gerin, & Thayer, 2006; Brosschot & Thayer, 2003).

While many research efforts have been devoted to the psychophysiological responding to negative emotions and stress (Cacioppo, Berntson, Larsen, Poehlmann, & Ito, 2000; Kreibig, 2010; Stemmler, 2004), the psychophysiology of mental load has been addressed less often. Since mental load, however, is the prevailing concept in pilot selection as well as routine flight (Goeters et al., 2004; Green, Muir, James, Gradwell, & Green, 2005), the present work concentrates on the psychophysiological assessment of mental load and its association with cognitive performance.

Gaillard (1993) argues that negative emotions might hinder the individual from focusing on task performance, whereas positive emotions or even low anxiety might increase motivation and lead to an optimal activation level.[2] This is supported by empirical evidence showing that anxiety (Eysenck & Calvo, 1992; Eysenck, Derakshan, Santos, &

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[2] In the present thesis, activation is used to describe the arousal level of an individual ranging from tired/calm to energetic/tense (see also Thayer, 1978).

Calvo, 2007) and neuroticism (Schneider, 2004) might impair cognitive functioning, while positive emotions have rather beneficial effects on attentional and processing capacities (Ashby, Isen, & Turken, 1999; Fredrickson & Branigan, 2005). Also Matthews and Davies (2001) report individual differences in the extent to which the availability of resources is affected by energetic arousal, but research on the association between physiological activation and performance is scarce and requires further elaboration. In the present work, performance measures were included for validation purposes, since cognitive performance is typically used as a suitable criterion for operator load in human factors and ergonomics. Especially knowledge about the poorly investigated relationship between respiration and cognitive performance could provide useful information for pilot selection and training (Karavidas, Lehrer, Lu, Vaschillo, Vaschillo, & Cheng, 2010; Lehrer, Karavidas, Lu, Vaschillo, Vaschillo, & Cheng, 2010).

## 2.1 Measuring mental load[3]

In order to monitor and predict operator performance, available research has revealed a number of different methods that can be assigned to three principle categories – rating scales, performance, and physiological measures – which are supposed to display particular aspects of mental load. This multifaceted understanding of mental load is supported by studies comparing the different workload measures which generally revealed low intercorrelations (DeLeeuw & Mayer, 2008; Eggemeier & Wilson, 1991; Miyake, Yamada, Shoji, Takae, Kuge, & Yamamura, 2009; Moray, 1982; Verwey & Veltman, 1996; Yeh & Wickens, 1988). Assuming that mental load is rather a composite than a unitary construct, it is recommended to combine various measures whenever possible. Moreover, a multivariate assessment allows balancing the advantages and disadvantages of each method as well as attaining maximum sensitivity and

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[3] In the field of human factors and ergonomics, the measurement of mental load and stress are usually not distinguished. In this section, we discuss the traditional measurement techniques of "mental load" according to the literature. The mentioned methodologies, however, have been used for the measurement of both mental load and task-induced stress.

diagnosticity[4] (Wierwille & Eggemeier, 1993; see also Miyake, 2001; Ryu & Myung, 2005; Wierwille, 1979).

*Rating scales*

Rating scale measures of mental load, often referred to as “subjective measures”, are inexpensive and easy to obtain. The level of mental load is rated by the operator himself after task completion or by an outside observer. Observer-based ratings can often be taken online. While ratings of outside observers are mainly based on visible performance and physiological strain symptoms such as sweating or a dry mouth, self-reports are based on operators’ feelings which are mainly related to the subjective probability of being able to satisfy task demands in terms of accuracy, payoff, speed, etc. (Ayres, 2006; Tulga, 1978). In addition, self-reports may also be related to experienced physiological changes such as heart rate or muscle tension. Economic aspects as well as high face validity are probably the main reasons why self-report measures are very popular in applied disciplines. However, in some situations individuals might be motivated to over- or underreport mental load in order to influence resultant decisions or to meet external expectations (Spector, 2012). In addition, self-ratings are susceptible to unintended bias and memory lapse (Spector, 2012). As reviewed and elaborated by Kazdin (1977), also observer-based ratings may be distorted by bias – especially if the observer is substantially involved as, for instance, in training situations.

*Performance measures*

Performance-based measures are mainly related to cognitive and motivational aspects of mental load. In computerized tasks, performance is often evaluated online and possibly reflects momentary changes and workload peaks. However, it is not possible to draw conclusions about the amount of invested effort and remaining operator capacity which might vary according to motivational states. The “dual-task paradigm” is an attempt to estimate remaining capacity by measuring performance on a secondary task. The

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[4] Diagnosticity describes the ability to determine different types of mental load.

operator is instructed to perform both tasks simultaneously but to prioritize the primary task. Assuming that both tasks require the same kind of cognitive and energetic resources, performance on the secondary task is then interpreted as a measure of remaining operator capacity. Major drawbacks of this method are that the actual interference of mental processes as well as the actual allocation of processing resources remains unclear (O'Donnell & Eggemeier, 1986). Since primary performance measures are more convenient to assess and interpret while having a strong operator acceptance, they are widely used for the evaluation of mental load.

### *Physiological measures*

When accomplishing a mentally demanding task, the operator is able to maximize his individual performance level by investing effort for a certain period of time. It is hence possible that an increased level of mental load is compensated for with additional energy expenditure. According to Wierwille (1979, p. 575), physiological arousal "may be considered as a state of preparedness of the body or level of activation of the human organism". However, it must be recognized that physiological arousal is not only affected by cognitive but also by emotional and motivational processes which are associated with mental load and thus part of the concept. The major value of physiological measures is that involuntary physiological changes index energetic and psychological processes, which are not comparably captured by ratings scales and performance-based measures (O'Donnell & Eggemeier, 1986). An additional assessment of physiological measures is particularly useful when self-reports are not feasible, prone to intentional or unintentional response biases, or when continuous measurements are required.

Parameters that have been studied for the assessment of mental load include electrical measures of brain activity, various measures of the cardiorespiratory system, skin temperature, electrodermal activity, cortisol level, pupil response, and parameters regulated by the somatic nervous system such as electromyographic measures (EMG) of muscle activation (Cain, 2007). In the present study we investigated heart rate (HR), heart rate variability (HRV), respiratory rate (RR), total variability (CV) and correlated variability (AR) of RR as well as partial pressure of end-tidal carbon dioxide (petCO$_2$). Their functioning and covariance with mental load are described in the following.

Cardiac measures:

HR is the number of contractions (heart beats) within one minute. Mental load is known to increase HR during difficult tasks (Backs & Seljos, 1994; Boucsein, Koglbauer, Braunstingl, & Kallus, 2011; Fournier, Wilson, & Swain, 1999; Turner, 1989; Veltman & Gaillard, 1996, 1998) by affecting vagal and sympathetic ways to the heart (e.g., Grossman, Stemmler, & Meinhardt, 1990; Porges & Byrne, 1992). Backs and Seljos (1994) assume that cardiac activity under mental load is increased by elevated energy expenditure in the brain and related metabolic processes, but the increase in HR appears to be much higher than the amount which can be explained by augmented metabolic activity (Carroll, Turner, & Hellawell, 1986; Turner & Carroll, 1985). Studies on the relationship between cardiac reactivity and task performance indicate that a stronger HR reactivity is associated with a better performance when dealing with complex tasks (Andreassi, 1966; Malmo, 1965; Mathewson et al., 2010).

The time interval between two successive heartbeats varies continuously. Oscillations in the HR pattern, called heart rate variability (HRV), are important for an organism to respond to environmental demands and to restore homeostasis. Greater amplitudes indicate more flexibility – why younger and healthy individuals usually show higher HRV (Friedman & Thayer, 1998; Park, Vasey, Van Bavel, & Thayer, 2014; Zhang, 2007). When performing mentally demanding tasks, HRV was found to be reduced (Aasman, Mulder, & Mulder, 1987; Backs & Seljos, 1994; Hansen, Johnsen, & Thayer, 2003; Mulder & Mulder, 1981; Vincente, Thornton, & Moray, 1987). This relationship has been replicated for a variety of mental tasks (see also Overbeek, van Boxtel, & Westerink, 2014). When performing complex tasks, a higher HRV during baseline has been reported to correlate with a better task performance (Hansen et al., 2003).

Respiratory measures:

The respiratory system is another important system to sustain internal balance. It is therefore contingent on external influences such as mental load. Central breathing reflexes which are controlled in the brain stem and spinal cord regulate arterial $pCO_2$ and pH levels in order to maintain homeostasis despite changing metabolic demands (Hasan, 2009). In addition, the respiratory pattern is subject to learning processes and sensitive to temporary emotional and cognitive influences that are mediated by neural factors and may lead to appropriate but also inappropriate changes (Bass & Gardner, 1985; Gallego, Nsegbe, & Durand, 2001). Compared to cardiovascular parameters such as HR and HRV, respiration has been investigated less intensively in the context of mental load. This is probably due to practical considerations, since most of the measurement techniques are obtrusive and the assessment and processing of respiratory data often more complicated. However, the existing empirical findings on respiration under mental load indicate the usefulness of respiratory parameters to evaluate mental load. Brookings, Wilson, and Swain (1996) consider respiratory rate to be one of the most sensitive measures of mental task demands. Findings on task related changes in RR are rather consistent in that participants breathe faster when performing mental laboratory tasks (Allen & Crowell, 1989; Brookings et al., 1996; Fournier et al., 1999; Pattyn, Migeotte, Neyt, van den Nest, & Cluydts, 2010; Vlemincx, Taelman, De Peuter, Van Diest, & Van den Bergh, 2011; Wientjes, Grossman, & Gaillard, 1998) and complex maneuvers in a jet cockpit or flight simulator (Karavidas et al., 2010; Wilson, 1993).

As well as for HRV, variations in the respiratory pattern result from continuous feedback mechanisms as well as anticipated changes, representing the capability to adjust to environmental demands. To what extent mental load might affect the variability in RR has been investigated only in a few studies so far. Vlemincx, Van Diest, and Van den Bergh (2012) report that, compared to baseline, sustained attention is accompanied by a decrease in total variability and that mental load, as induced by mental arithmetic, is related to a decrease in correlated variability and an increase in total variability.[5]

The $etCO_2$ level indicates whether ventilation is appropriate to the current metabolic demand. Arterial $pCO_2$ is normally maintained at a level of 40 mmHg. If ventilation exceeds metabolic demands (hyperventilation), the mismatch between respiratory rate and depth causes alkalosis and a decrease in arterial and alveolar $pCO_2$.[6] Due to vasoconstriction, oxygen supply to the brain is reduced which may elicit a variety of somatic symptoms (Grossman & Wientjes, 1989) and impaired cognitive performance (Gibson, 1978; Van Diest et al., 2000). In a study conducted by Matthews, Warm, Reinerman-Jones, Langheim, Washburn, and Tripp (2010), cerebral blood flow velocity predicted performance in demanding vigilance tasks that required monitoring and working memory skills. Slower cerebral blood flow and related performance decrements, however, appear to occur only under hypocapnic and not normocapnic hyperventilation[7] (Bloch-Salisbury, Lansing, & Shea, 2000; Hida, Kikuchi, Okabe, Miki, Kurosawa, & Shirato, 1996; Marangoni & Hurford, 1990; Rahn, Otis, Epstein, Hunter, & Fenn, 1946). Karavidas et al. (2010) report that challenging simulated flight maneuvers can lead to hypocapnic hyperventilation in experienced pilots. However, it cannot be concluded that performing a mental task in the assessment situation has a similar impact on the candidates' respiratory pattern. Only a few studies using a highly demanding mental task investigated $etCO_2$. Wientjes et al. (1998), for instance, report a significant but small

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[5] The total variability in RR is considered to compound a correlated, structured portion that is usually determined on a breath-to-breath basis for a defined period (Tobin, Yang, Jubran, & Lodato, 1995) and an uncorrelated, random portion which has been quantified by subtracting the correlated fraction from total variability measures such as statistical variance or the coefficient of variation (e.g., Vlemincx et al., 2011).

[6] Alveolar $pCO_2$ is regarded as a valid approximation of arterial $pCO_2$ in spontaneous breathing, healthy individuals (Phan, Tremper, Lee, & Barker, 1987; Takano, Sakamoto, Kiyofuji, & Ito, 2003) and closely correlated with the plateau values of $pCO_2$ at the end of expiration ($petCO_2$) (Wientjes, 1992). The $petCO_2$ level is thus used as a noninvasive estimate of alveolar $pCO_2$.

[7] Hyperventilation describes a breathing pattern which exceeds metabolic demands and leads to an increase in blood pH (alkalosis) and a decrease in blood $CO_2$. "Normocapnia" means that $petCO_2$ values are at normal level or only slightly reduced, whereas "hypocapnia" is typically used for $petCO_2$ values below 32 mmHg.

decrease in $petCO_2$ from baseline to a difficult memory task. In the field of aviation, existing studies suggest that end-tidal and transcutaneous $pCO_2$ levels might be sensitive to workload changes of characteristic job demands (Harding, 1987; Wientjes, Gaillard, & ter Maat, 1996), but further exploration of these findings is required – especially when taking recent developments in $etCO_2$ sampling techniques into account.

## 2.2 Interindividual differences

Apart from attentional, processing, and energetic capacities, individuals differ in how they evaluate a given situation. A person with high trait anxiety may perceive a test situation as threatening, whereas the appraisal of a low anxious and self-confident person may be positive and challenging. Depending on how external demands and internal coping abilities are evaluated, individuals are assumed to show physiological reactivity indicating energy mobilization due to the activation of additional mental resources ("trying harder") or stress-related affective processes (fight-or-flight response).

Accordingly, the concept of individual response specificity (Lacey, Bateman, & Van Lehn, 1953) states that physiological reactivity to a certain stressful situation differs between individuals. While some tend to have relatively stable response specificity, others show changes in their response pattern to stress (Marwitz & Stemmler, 1998; Wenger, Clemens, Coleman, Cullen, & Engel, 1961). Interindividual variation in physiological reactivity is supposed to originate from biological factors (i.e., differences in neural systems and genes; Lovallo & Gerin, 2003; Turner, 1989) as well as from environmental factors. Environmental factors again are mediated by psychological processes, since it is the perception or rather the internal representation of the environment – again sharing variance with biogenetic factors – that influences personality (Seery, 2011; Stemmler & Wacker, 2010).

Beyond theoretical considerations, it is suggested by laboratory and field research on psychophysiological reactivity that the concept of interindividual differences is central to the measurement of mental load (Fahrenberg, Foerster, Schneider, Müller, & Myrtek, 1986; Manuck, Kamarck, Kasprowicz, & Waldstein, 1993; Saus, Johnsen, Eid, & Thayer, 2012; Szymura & Wodniecka, 2003). Nevertheless, most studies in the field of human factors and ergonomics still disregard individual differences, assuming that autonomic reactivity is independent of operator characteristics (Szalma, 2009) and, as a consequence, treating unexplained variance as noise or error variance (Karwowski et al., 2003).

Empirical investigation of the sources of interindividual variation in psychophysiological reactivity is mainly restricted to the concept of stress; several studies also combine mental, emotional, and physical stressors in their experimental design. Chida and Hamer (2008) surveyed the literature from 30 years of research on physiological reactivity to laboratory-induced stress. They found anxiety as well as neuroticism to be associated with a decreased cardiovascular reactivity, but also to be associated with a slower recovery. Other researchers reported an increased physiological response to stress for individuals scoring high on neuroticism (Schwebel & Suls, 1999), worry (Brosschot, Gerin, and Thayer, 2006; Ottaviani et al., 2015), and avoidant coping style (King, Taylor, Albright, & Haskell, 1990; Weinberger, Schwartz, & Davidson, 1979). A review by Myrtek (1998) of ten years of research on the association between personality traits and physiological reactivity to stress revealed some significant findings for extraversion and neuroticism but effect sizes were small to moderate, implying a more extensive approach when investigating interindividual differences. This is also indicated by theoretical concepts of individual differences which assume an interaction of personality traits and situational characteristics. Stemmler and Wacker (2010) argue that the individual appraisal of a stressful situation evokes "contextualized" dispositions (e.g., neuroticism, coping strategies) which in turn elicit a behavioral response such as certain levels of arousal and test performance (see also Humphreys & Revelle, 1984; Mischel & Shoda, 1995; Seery, 2011, 2013; Stemmler, 1997).

Moreover, there is evidence that "verbal-autonomic response dissociations", the relationship between self-reported and autonomic measures of mental load, are partly inherent to the person (Manuck & Garland, 1980; Newton & Contrada, 1992; Schwerdtfeger, Schmukle, & Egloff, 2006; Tomaka & Blascovich, 1994). Therefore, an incorporation of individual characteristics such as personality traits also appears to be relevant when combining physiological measures with self-reports of mental load which is often done for both research and application purposes.

Taken together, theoretical assumptions and empirical findings suggest that an investigation of interindividual differences in psychophysiological reactivity to mental load should include direct and interactive relationships between trait characteristics, affective states, and autonomic arousal in order to increase the validity of workload measurements.

# 3 Research questions

The main objective of this thesis was to refine the assessment of mental load in pilot selection and to evaluate the usefulness of cardiorespiratory parameters for the measurement of operator load.

Since mental load and stress are often confounded in the literature on human mental workload, we conducted a review study on respiratory effects specifically for mental load in order to provide a firm basis for future research (Chapter 4). The purpose was to evaluate whether respiratory measures are sensitive to (a) baseline-to-task changes and (b) different levels of task difficulty. In addition, we integrated findings on the effect of task duration. Possible habituation effects would be relevant for both studying and using respiratory parameters as indicators of mental load. Since concurrent performance feedback has been hypothesized to be a prerequisite for accomplishing a mental task (Hockey, 1986; Wientjes, Grossman, & Gaillard, 1998) but also to cause stress (Gaillard & Wientjes, 1994; Jerusalem & Schwarzer, 1992; Light & Obrist, 1980), we further investigated whether empirical evidence suggests that respiratory reactivity to mental load is impacted by concurrent performance feedback.

The analyses presented in Chapters 5 and 6 are based on an experimental cardiorespiratory study we conducted with 115 pilot candidates who volunteered to participate subsequent to their aptitude testing for a civilian airline. The experiment consisted of a resting baseline, a vanilla baseline, a highly demanding computerized multiple task, and a recovery period. The vanilla baseline was additionally included to reduce possible effects of anticipatory arousal by means of a simple vigilance task (Jennings, Kamarck, Stewart, Eddy, & Johnson, 1992). In order to induce mental load that is comparable to task demands of pilot selection and pilot training, the multiple task combined three typical cognitive requirements of routine airline flights in a simplified manner. While self-report, performance, and cardiac measures were obtained for the entire sample, respiratory measures could only be recorded in a subsample of 61 participants.[8] Given that respiratory measures have rarely been studied as correlates of mental load, our first analyses (Chapter 5) aimed at evaluating the sensitivity of respiratory rate, variability in respiratory rate, and $petCO_2$ to mental load. In addition, we investigated whether task-related changes in respiration covary with cognitive performance measures in order to draw conclusions for future methods in pilot selection.

Since operator characteristics have often been neglected as potential confounding variables of autonomic arousal, we conducted a further series of analyses to elaborate on individual differences in cardiac and respiratory measures of mental load (Chapter 6). A primary aim was to investigate whether differences in the autonomic parameters assessed during resting states and mental load can be explained by personality traits, which are supposed to covary with individual coping resources as well as physiological arousal. Since autonomic measures are often combined with self-reported mental load and affect (e.g., for validation purposes), a second aim was to determine the influence of personality traits on the relationship between cardiorespiratory and self-report measures of mental load.

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[8] Due to the fact that the laboratory equipment comprised only one capnograph and that usually two participants were assessed in parallel.

# 4 Respiratory changes in response to mental load
# A systematic review

Based on: Grassmann, M., Vlemincx, E., von Leupoldt, A., Mittelstädt, J. M., & Van den Bergh, O. (submitted). Respiratory changes in response to cognitive load: A systematic review.

## 4.1 Abstract

Because respiration is sensitive to changes in cognitive and emotional demands, we conducted a systematic review of empirical studies investigating respiratory behavior in response to mental load. Most reviewed studies were restricted to time and volume parameters while less established, yet meaningful parameters such as respiratory variability and gas exchange measures have rarely been investigated. The available results show that respiratory behavior generally reflects cognitive processing and that distinct parameters differ in sensitivity: While mentally demanding episodes are clearly marked by faster breathing and higher minute ventilation, the respiratory amplitude appears to remain rather stable. The present findings further indicate that the total variability in respiratory rate is not systematically affected by mental load whereas the correlated fraction decreases. In addition, we found that mental load may lead to overbreathing, as indicated by decreased end-tidal $CO_2$ levels, but is also accompanied by elevated oxygen consumption and $CO_2$ release. However, additional research is needed to validate the findings on respiratory variability and gas exchange parameters, since most of the reviewed studies only focused on traditional time and volume parameters. We conclude by outlining recommendations for future research to increase our understanding of respiratory changes under mental load.

## 4.2 Introduction

In human factors and ergonomics, the investigation of mental load aims at predicting operator performance (e.g., pilot selection) and optimizing working conditions (e.g., cockpit design) in order to enhance performance and comfort. For this purpose, physiological parameters have been considered as valid indicators of mental load since they are hypothesized to reveal task-related arousal in the operator.

Mental load is assumed to be high when the required resources for a satisfactory task completion come up against the limits of operator capacity (Gopher & Donchin, 1986; Kantowitz, 1987; O'Donnell & Eggemeier, 1986). Importantly, the concept of mental load should be differentiated from mental stress. As pointed out by Gaillard and Wientjes (1994), arousal due to mental stress is characterized by negative feelings such as anxiety or frustration while mental load is accompanied by neutral or even positive feelings as being challenged. Both concepts assume that the individual experiences some discrepancy between environmental demands and one's coping resources and initiates extra effort. Under mental load, the individual focuses on accomplishing the task and on performance monitoring whereas under stress, the individual is mainly concerned with threats and protection of the self. In the literature, however, the two concepts are often confounded in terms of terminology or experimental implementation (Gaillard, 1993).

For the manipulation of mental load, researchers typically apply cognitive tasks such as mental arithmetic or Stroop tests. These tasks have in common that they involve several aspects of cognitive processing as, for instance, perception, controlled attention, reasoning, memory, problem solving, decision making, and inhibitory control, as well as cognitive control of speech and motor activity inasmuch as this is required for performance. Study designs differ in whether a concurrent performance feedback is provided or not. On the one hand, researchers argue that permanent feedback is necessary for an individual's monitoring of the process and a corresponding regulation of energetic state (Hockey, 1986; Wientjes et al., 1998). On the other hand, performance feedback while accomplishing the task may cause psychological stress in addition to the mental task demands (Gaillard & Wientjes, 1994; Jerusalem & Schwarzer, 1992; Light & Obrist, 1980).

### *The measurement of mental load*

Investigating the concept of mental load dates back to the 1970s (Huey & Wickens, 1993) and has generated a broad number of different methods that are generally categorized into rating scale measures, performance-based measures, and physiological measures (O'Donnell & Eggemeier, 1986). In the past, self-report measures have often been regarded as less reliable and valid than "objective" performance scores and physiological data (Gopher & Donchin, 1986), but today's prevailing view considers the different methods as reflecting different aspects of operator load. As a consequence, present research and real-life assessments in human factors and ergonomics are usually based on a combination of self-report, performance, and physiological measures.

Respiration is the biggest oscillator in the body involved in regulating processes in response to environmental demands and thus maintaining homeostasis. Respiratory activation not only indexes metabolic changes but also psychological and behavioral processes (Wientjes et al., 1998). However, existing reviews on physiological correlates of mental load show that research efforts have mainly been devoted to cardiovascular, electrodermal, and brain activity (Cain, 2007; Kramer, 1991; Manzey, 1998; Wierwille, 1979). Apart from that, Wientjes et al. (1998) claimed that many of the available studies on respiration applied rudimentary measurement techniques. More recent studies, however, have adapted assessment methods from respiratory physiology and integrated more sophisticated parameters providing additional insights into breathing behavior under mental load (e.g., variability measures, see Vlemincx et al., 2011).

### *Quantifying respiration*

#### Respiratory measures:

In general, research in respiratory psychophysiology in healthy populations is based on measures reflecting time, volume, and gas exchange aspects of breathing. The most common parameters are respiratory rate (RR) and respiratory amplitude which corresponds to tidal volume (TV), the amount of air that is inspired during one respiratory cycle. Minute ventilation (MV) refers to the amount of air that is inhaled in one minute and is hence contingent upon RR and TV. Further time and volume parameters that are analyzed frequently are inspiratory time ($T_i$), expiratory time ($T_e$), as well as inspiratory volume ($V_i$) which equals TV and expiratory volume ($V_e$) and the timing ratio of inspiration to expiration ($T_i/T_e$). Also mean inspiratory flow rate ($TV/T_i$)

and inspiratory duty cycle ($T_i/T_{tot}$) are occasionally calculated, both quotients indicating the activity of underlying respiratory drive mechanisms (see Boiten, Frijda, & Wientjes, 1994). Specific response measures such as sigh rate (SR) and the proportion of ribcage breathing to $V_i$ (%RCi) have rarely been reported in the literature. In addition to basic time and volume parameters, corresponding variability measures have been computed to quantify total variability by using statistical variance (Var) or the coefficient of variation (CV) as well as structured variability by using the autocorrelation (AR) of successive breaths. Since total variability is considered to comprise structured and random portions (Vlemincx, Abelson, Lehrer, Davenport, Van Diest, & Van den Bergh, 2013; Vlemincx et al., 2011) which might be affected differently by environmental demands, total variability measures should be interpreted together with a measure of correlated variation. Among the gas exchange parameters, partial pressure of end-tidal carbon dioxide ($petCO_2$), an estimate of arterial $pCO_2$, is particularly interesting since reduced $CO_2$ values generally indicate that ventilation is in excess of metabolic need. Also oxygen consumption ($VO_2$) and $CO_2$ production ($VCO_2$), which usually covary with MV, as well as the proportion of released $CO_2$ to inhaled $O_2$ (respiratory exchange ratio; RER) have been investigated to determine energy expenditure in demanding situations.

Since most of the outlined measures may vary with age, gender, and physical fitness, it is useful to take possible control variables into account when investigating respiratory reactivity in healthy individuals (Cardús, et al., 1997; Chen & Kuo, 1989; de Geus, Van Doornen, de Visser, & Orlebeke, 1990; White, Douglas, Pickett, Weil, & Zwillich, 1983). Apart from person-related covariates, verbal activity during data acquisition can influence time and volume parameters. Speech production requires a coordination of articulatory and respiratory movements which typically leads to a shorter $T_i$, accompanied by increased airflow velocity, and to a longer expiratory time together with decreased airflow velocity (Conrad & Schönle, 1979; Winkworth, Davis, Ellis, & Adams, 1994). In addition, speech and motor activity can cause artifacts in the recording process. While spirometric and capnographic methods directly sampling from mouth and nose are inevitably affected by vocal activity, electronic signals of impedance-based methods are particularly prone to motion (Pawar, Anantakrishnan, Chaudhuri, & Duttagupta, 2007; Qu, Zhang, Webster, & Tompkins, 1986). As a consequence, most researchers counter such artifacts by selecting tasks that require a minimum of speech and motor activity and by instructing participants not to talk or move during the periods of data acquisition, unless it is required.

Apparatus:

General measurement techniques to quantify respiration in healthy individuals comprise spirometry, respiratory inductive plethysmography, strain gauges, impedance-based methods, capnography, and metabolic analyzers. While all these techniques are usually suited to record timing parameters, the amplitude of breathing can only be assessed by a direct measurement of lung volume (using spirometry) or indirectly through changes in girth of thorax and abdomen (using strain gauges or respiratory inductive plethysmography) or through changes in impedance of the thorax. Spirometric devices such as spirometers, flowmeters, and pneumotachographs provide accurate assessments of $V_i$ and $V_e$, but also require participants to wear a facemask, a mouth- or noseclip that, in itself, may alter the respiratory behavior (Perez & Tobin, 1985). Most common is the use of inexpensive strain gauges, converting mechanical strain into voltage, and inductive plethysmography, measuring self-inductance in transducer bands. Both techniques are unobtrusive and easy to handle. However, without a constant and valid calibration procedure they do not provide absolute measures of respiratory depth. The same applies to impedance plethysmography which additionally is rather expensive. Hence, it has been suggested to estimate RR and amplitude by means of spectral analysis from the impedance cardiography signal (de Geus, Willemsen, Klaver, & van Doornen, 1995; Ernst, Litvack, Lozano, Cacioppo, & Berntson, 1999; Houtveen, Groot, & de Geus, 2006) since respiratory and cardiac monitoring are often combined. $PetCO_2$ is mainly assessed by means of a capnograph with infrared spectrography and a sampling site that is attached to the mouth and/or nose. For the combined determination of $VO_2$ and $VCO_2$, metabolic measurement systems are used which commonly are equipped with paramagnetic $O_2$ and infrared $CO_2$ sensors. Due to the direct sampling from mouth and nose, also capnographs and metabolic analyzers are rather intrusive but, on the other hand, they provide accurate and absolute assessments of respiratory parameters.

*The present study*

The objective of this review was to provide an overview on empirical studies examining the respiratory effects of mental load for research and application purposes such as monitoring operator load. Specifically, we aimed at analyzing all published results provided by a search in electronic databases that investigated changes in at least one respiratory measure from a baseline to a task period characterized by any kind of mental load. We further integrated findings on respiratory sensitivity to different levels of task difficulty as well as findings on the effect of task duration. Finally, we made a comparative evaluation of respiratory reactivity under experimental conditions with and without concurrent performance feedback.

## 4.3 Literature research and study selection

Electronic database searches of PsycINFO, PubMed, and Web of Science were conducted using the following terms without a priori publication date restrictions:

[mental OR cognitive OR attentional] AND [load OR workload OR stress OR effort] AND [respirat* OR breath* OR $CO_2$]

This query yielded 819 references. After an examination of title and abstract, 636 irrelevant sources were excluded. The remaining 183 references were subjected to a detailed screening based on the full papers. We selected journal publications in English language reporting original data on respiratory measures in response to mental task load. Study samples had to consist of healthy adult participants, breathing spontaneously during at least one period of data acquisition under mental load. Clinical studies and experiments that entailed physical activity, emotion induction, physical or psychosocial stress (e.g., cold pressor, public speech), manipulated or controlled breathing, or pharmaceutical intervention were only selected if respiratory data were reported for a control group or control condition (i.e., spontaneous breathing without any manipulation other than mental load), respectively. For those studies, only data from the control group and/or control condition were taken into account. Further inclusion criteria were data acquisition during rest for the analysis of baseline-to-task changes as well as a limited level of movement activity and speech, which might in itself impose respiratory changes. Strictly speaking, studies were excluded if participants were allowed to move and/or speak more than briefly indicating a required task response by moving a mouse cursor or saying a single word or number.

The study selection was conducted independently by two authors to ensure reliable data acquisition (Moher, Liberati, Tetzlaff, & Altman, 2009). If authors disagreed, the procedure was repeated for the corresponding reference after discussing the prevailing concern. References with divergent ratings after the second screening were classified through consensus discussion.

## 4.4 Data extraction and synthesis

A total of 53 journal articles evaluating respiratory parameters in response to mental task load and meeting the selection criteria were included in this review. Study characteristics and findings were extracted from every publication and listed. During the process of data acquisition and integration, this list was completed with additional variables that appeared relevant and eventually covered the following information: first author, publication year, sample size and characteristics, type of experimental manipulation, duration of analyzed task period, respiratory outcome measures and measurement techniques, additional information on verbal activity and performance feedback, as well as the reported findings on respiratory changes in response to mental task load including possible effects of task difficulty and duration (if analyzed).

*Study characteristics*

Table 1 summarizes the study characteristics of 54 experiments which are reported in 53 articles. Sample sizes ranged between 7 and 132 participants with a mean of 32 participants. The experimental tasks to induce mental load were categorized according to the cognitive processes primarily required for accomplishing the task (i.e., attention, reasoning, short-term or working memory, psychomotor coordination, vigilance) or according to the respective task type/paradigm if more than one major facet of cognitive control was required (i.e., Stroop, mental arithmetic, choice reaction time, multi-tasking).

Operator load was most often manipulated by administering mental arithmetic or multiple tasks, followed by attention, memory, Stroop, reasoning, and psychomotor tasks. As depicted, RR is the only variable that has been analyzed in all studies under review. Apart from TV and MV, all other parameters have been evaluated in less than 10% of the studies. To collect respiratory signals, most of the studies used a strain gauge or an inductive plethysmograph which are not intrusive and relatively easy to handle. However, spirometry, capnography, and impedance plethysmography were also conducted in at least five of the reviewed studies.

Table 1. Characteristics of selected studies (*N* = 54).

| | No. of studies | % of studies |
|---|---|---|
| Sample | | |
| Average size (range) | 32 (7–132) | |
| Males | 21 (3–64) | |
| Females | 20 (1–68) | |
| Characteristics | | |
| Male only | 14 | 25.93 |
| Female only | 3 | 5.56 |
| Mixed gender | 37 | 68.52 |
| Mean age in yrs (range) | 27.08 (18–80) | |
| Manipulation (type of cognitive task) | | |
| Mental arithmetic | 17 | 25.93 |
| Stroop interference | 5 | 9.26 |
| Memory | 6 | 11.11 |
| Reasoning | 6 | 11.11 |
| Psychomotor | 5 | 9.26 |
| Multi-tasking | 14 | 25.93 |
| Choice reaction time | 2 | 3.70 |
| Attention | 9 | 16.67 |
| Vigilance | 2 | 3.70 |
| Respiratory measures | | |
| Respiratory rate (RR) | 54 | 100.00 |

Table 1. Continued.

| | No. of studies | % of studies |
|---|---|---|
| Tidal volume (TV) | 24 | 44.44 |
| Minute ventilation (MV) | 9 | 16.67 |
| Inspiratory time ($T_i$) | 1 | 1.85 |
| Expiratory time ($T_e$) | 0 | 0.00 |
| Inspiratory/expiratory ratio ($T_i/T_e$) | 1 | 1.85 |
| Mean inspiratory flow rate ($TV/T_i$) | 1 | 1.85 |
| Inspiratory duty cycle ($T_i/T_{tot}$) | 3 | 5.56 |
| Expiratory volume ($V_e$) | 1 | 1.85 |
| Contribution of ribcage breathing to $V_i$ (%RCi) | 2 | 3.70 |
| Sigh rate (SR) | 2 | 3.70 |
| Respiratory variability | | |
| Variance of RR (Var (RR)) | 1 | 1.85 |
| Coefficient of variation of RR (CV (RR)) | 3 | 5.56 |
| Autocorrelation of RR (AR (RR)) | 3 | 5.56 |
| Coefficient of variation of TV (CV (TV)) | 2 | 3.70 |
| Autocorrelation of TV (AR (TV)) | 2 | 3.70 |
| Coefficient of variation of MV (CV (MV)) | 2 | 3.70 |
| Autocorrelation of MV (AR (MV)) | 2 | 3.70 |
| Partial pressure of end-tidal $CO_2$ ($petCO_2$) | 4 | 7.41 |
| $O_2$ consumption ($VO_2$) | 4 | 7.41 |
| $CO_2$ production ($VCO_2$) | 4 | 7.41 |
| Respiratory exchange ratio (RER) | 2 | 3.70 |
| Apparatus | | |
| Spirometry | 7 | 12.96 |
| Respiratory inductive plethysmography | 15 | 27.78 |
| Strain gauge | 19 | 35.19 |
| Impedance plethysmography | 4 | 7.41 |
| Impedance cardiography | 3 | 5.56 |
| Capnography | 6 | 11.11 |
| Metabolic analyzer | 2 | 3.70 |

A detailed list of the studies included in the present review is shown in Table A (Appendix). As indicated, the duration of task period that was extracted for data analysis varied between 30 and 1800 sec, with 57% of the studies choosing sampling periods lasting between 180 and 300 sec. Four of the seven studies requiring a verbal task response systematically investigated the effect of verbal activity on respiratory changes under mental load (# 7; 8; 9; 43; see Table A for numbering of studies). A concurrent performance feedback was given in 35% of the studies. One of these studies systematically compared respiratory reactivity to mental task load with and without performance feedback (# 54).

### *Coding and integration of effects*

To integrate the findings on respiration under mental load we coded baseline-to-task changes for every respiratory outcome measure as increasing (↑), decreasing (↓), or not significantly changing (–) at $p < .05$. If a study included more than one experimental period (trial), reported findings were counted according to the number of trials (e.g., twice if a study reported an increase in two trials). Table 2 displays overall effects as reported by more than 50% of the reviewed studies. If two different effects were revealed by an equal number of studies or experimental periods (e.g., increase and decrease were found in five studies each), we coded the overall effect accordingly as ↑↓, ↑–, or ↓–. The same procedure was applied to review respiratory changes in response to different levels of task difficulty ($n = 15$) as well as changes in respiratory reactivity over time ($n = 6$).

In order to evaluate the magnitude of effects, we computed standardized mean differences for every significant baseline-to-task change for which the required descriptive data were available. In sum, 50% of the reviewed studies reported their significant findings together with mean (*M*) and standard deviation (*SD*) or standard error (*SE*) scores for either baseline and task conditions or for the discrepancy between baseline and task. As a measure of effect size, we calculated whenever feasible Cohen's *d* using pooled *SD* and adjusted for small sample bias if less than 50 participants were included in the reported analysis (Durlak, 2009). In the following, we present the integrated effects for each respiratory measure. Effect sizes are evaluated if (a) the overall effect for the respective measure indicates an increase or decrease, and (b) at least one study conforming to the overall effect was available for calculating Cohen’s *d*.

### *Empirical findings on respiration and mental load*

As shown in Table 2, the breathing pattern under mental load was mainly characterized by faster respiration than during baseline. Following the guideline by Cohen (2009), five studies suggest small effects ($.20 \leq d < .50$; # 4; 6; 7; 50; 53), six studies medium effects ($.50 \leq d < .80$; # 6; 22; 23; 28; 31; 50), and 20 studies large effects ($d \geq .80$; # 1; 4; 5; 7; 13; 16; 20; 25; 26; 27; 28; 30; 35; 36; 39; 42; 43; 44; 46; 52) for the increase in RR. For one study, the calculated effect size indicates that the significant increase in RR while performing a vigilance task can be considered negligible ($d = .12$; # 39). Table 2 further shows that higher task difficulty resulted in an additional increase of RR. Those studies providing data for calculating effect sizes on different levels of task difficulty indicate that the increase in RR changed from small to medium effects (# 6) and from medium to large effects (# 4; 28) when the task became more difficult in a parallel fashion.

Table 2. Overview of respiratory changes in response to reviewed mental tasks.

| | Changes from baseline to task ($N = 54$) | Changes with increasing task difficulty ($n = 14$) | Reactivity over time/trials ($n = 6$) |
|---|---|---|---|
| RR | ↑ | ↑ | ↓– |
| TV | – | – | (–) |
| MV | ↑ | (–) | |
| $T_i$ | (↓) | (–) | |
| $T_i/T_e$ | (–) | | |
| $TV/T_i$ | (↑) | | |
| $T_i/T_{tot}$ | (↑–) | | |
| $V_e$ | (↑) | | |
| %RCi | (–) | | |
| SR | (↑–) | | |
| Respiratory variability | | | |
| Var (RR) | (↓–) | (–) | |
| CV (RR) | (–) | | (–) |
| AR (RR) | ↓ | | (–) |
| CV (TV) | (↑) | | (–) |
| AR (TV) | (–) | | (–) |
| CV (MV) | (–) | | (–) |
| AR (MV) | (–) | | (–) |
| $petCO_2$ | ↓ | | |
| $VO_2$ | ↑ | (–) | |
| $VCO_2$ | (↑) | (↑) | |
| RER | (↑↓) | | |

*Note*. ↑: increase, ↓: decrease, –: no change. A combination of two characters indicates that the corresponding effects were reported by an equal number of studies. Parentheses indicate a database of less than three studies for increase, decrease, no change, and mixed effects, respectively. RR: respiratory rate, TV: tidal volume, MV: minute ventilation, $T_i$: inspiratory time, $T_i/T_e$: inspiratory/expiratory ratio, $TV/T_i$: mean inspiratory flow rate, $T_i/T_{tot}$: inspiratory duty cycle, $V_e$: expiratory volume, %RCi: contribution of ribcage breathing to inspiratory volume, SR :sigh rate, Var: variance, CV: coefficient of variation, AR: autocorrelation, $petCO_2$: partial pressure of end-tidal carbon dioxide, $VO_2$: oxygen consumption, $VCO_2$: carbon dioxide production, RER: respiratory exchange ratio.

While the studies including TV are rather inconsistent and mainly reported no significant changes from baseline to task, MV increased in all studies with two studies suggesting large effects (# 1; 22) and one study suggesting a small effect (# 50) for the increase in MV. MV was not related to varying difficulty levels. Overall, reactivity patterns were further marked by a reduced correlated variability (AR) of RR with two studies indicating medium effects (# 20; 50), whereas total variability (Var, CV) of RR was mostly invariant to mental load. Capnographic measures show that $petCO_2$ levels were lower during task performance (*d* = – .26; # 20), while $VO_2$ as well as $VCO_2$ were higher during the task and $VCO_2$ additionally elevated with increasing difficulty. Effects sizes for the increase in $VO_2$ ranged from small (# 5; 25) to medium and large effects (# 1), and from medium (# 6) to large effects (# 1) for the increase in $VCO_2$. The available data suggest that both low and high levels of task difficulty elicited a medium increase in $VCO_2$ from baseline to task (# 6). The two studies including RER revealed opposite results, one increasing and one decreasing from baseline to task. Habituation effects were only reported for RR. However, the same number of studies provides support that elevations in rate persisted over time or from trial to trial. Across all trials, the analyzed task period averaged 1550 sec for the studies indicating habituation and 2270 sec for the studies reporting no change in reactivity.

Respiratory reactivity effects published in the seven studies that required verbal responding to the mental task (# 6; 7; 8; 9; 12; 32; 53) largely correspond with the overall effects: an elevated RR (available effect sizes are provided below) and no change in respiratory waveform ($T_i/T_e$). TV, however, was found to decline from baseline to tasks with verbal responding in one out of three studies analyzing TV (# 53). The only study including respiratory variability reported a decrease in total variability in RR, which is not line with the overall effects outlined above (# 32). In addition, it has to be noted that the systematic investigation revealed significant differences between "silent" and "aloud" conditions in three out of four studies: In one study, RR was found to be increased only in the "aloud" condition of a Stroop interference task (*d* = 6.40; # 7) while in two other studies, rate was found to be increased only in the "silent" condition of a mental arithmetic task (*d* n/a; # 8; *d* = 1.88; # 43). Furthermore, a reduced TV has been reported exclusively when participants remained silent (# 8), which conflicts with the finding mentioned above (# 53), as well as a reduced $T_i/T_e$ when participants indicated their response verbally (*d* n/a; # 8).

When comparing the respiratory measures from experimental conditions with and without concurrent performance feedback that were investigated by a minimum of three studies, we found for both conditions an increase in RR and in MV from baseline to task. Effect sizes were available for ten studies with at least one feedback condition, suggesting small (# 6; 50; 53) as well as medium (# 6; 22; 23; 31; 50) and large effects (# 13; 30; 44; 52) for RR and small (# 50) as well as large (# 22) effects for MV. The available 16 studies with at least one no-feedback condition mainly suggest large effects for RR (# 1; 4; 5; 7; 16; 20; 25; 26; 27; 28; 35; 36; 39; 42; 43; 46) and MV (# 1). Interestingly, the implementation of feedback was mostly associated with a decrease in TV, two studies indicating small effects ($d = -.27$; # 54; $d = -.26$; # 50) and one indicating a large effect ($d = -2.51$; # 12), whereas the experiments not providing feedback did not show significant changes in TV. The direct comparison of feedback and no-feedback conditions within a single experiment revealed no significant differences in reactivity for any respiratory parameter under study (RR, TV, MV, $TV/T_i$, $T_i/T_{tot}$, $petCO_2$; # 54).

## 4.5 Discussion

This study was conducted to review the available literature on respiration under mental load by integrating findings on respiratory changes from baseline to task and possible effects of task difficulty, task duration, and concurrent performance feedback. In addition, we surveyed the methods used to manipulate mental load and to quantify respiration and separately analyzed respiratory changes from baseline to tasks that required verbal responses.

### *Respiratory responses to mental load*

The present findings show that mental load was accompanied by a clear increase in RR. Of note, 48% of the reviewed studies indicated medium to large effects for the increase from baseline to task. Also, higher levels of task difficulty resulted in an additional increase of RR. While TV appeared to be insensitive to mental load, MV – following logically from the increase in RR without changes in TV – showed a consistent increase from baseline to task. This general increase in ventilation has been explained by a higher metabolic rate during performance (Backs & Seljos, 1994) but also by psychological processes such as learned anticipation of metabolic need (Stegen, De Bruyne, Rasschaert, Van de Woestijne, & Van den Bergh, 1999; Tobin, Perez, Guenther, D'Alonzo, & Dantzker, 1986; Zaman, Van den Bergh, Fannes, & Van Diest, 2014). Since MV was not sensitive to different levels of task difficulty and predominantly reflects the increase RR, we conclude that, for the assessment of operator load, MV does not provide incremental information over the more convenient frequency measure.

The timing parameters discussed in the following have been investigated by less than three studies and should thus be interpreted with caution. Considering the increase in RR, a shorter $T_i$ and an invariant ratio of $T_i$ to $T_e$ signify a shortening of both $T_i$ and $T_e$ under mental load. The reported increase in TV/$T_i$ was observed together with no changes in $T_i/T_{tot}$ (Wientjes et al., 1998), indicating that the overall elevations of ventilation are rather caused by a higher "intensity of the central inspiratory drive mechanism" (Boiten et al., 1994, p. 106) than by alterations in timing. However, Pattyn et al. (2010) provide support that also the timing mechanism might trigger the increase in ventilation under mental load, suggesting that additional studies are needed to clarify the underlying mechanisms of ventilatory changes.

Frequency of sighing under mental load was investigated by two studies (Vlemincx et al., 2011; Vlemincx et al., 2012) showing that SR increased in response to mental arithmetic. The authors suggest that sighing counteracts erratic breathing patterns which may occur under mental load. Also in the present study, mental load consistently elicited a decrease in correlated variability in RR while, overall, total variability in RR did not change from baseline to task. This implies that random variability tends to increase when performing a cognitive task. Evaluating variability measures of TV and MV mainly revealed no changes from baseline to task. Only total variability in TV has been reported to increase considerably during mental arithmetic (Vlemincx et al., 2011; Vlemincx et al., 2012).

Moreover, mental load was shown to be associated with reduced petCO$_2$, indicating hyperventilation, and higher levels of VO$_2$ as well as VCO$_2$, which are usually assessed to track energy expenditure. The decrease in petCO$_2$ and the increase in VCO$_2$ appear to be conflicting. It has to be noted, however, that petCO$_2$ is a fractional measure, not allowing conclusions about absolute CO$_2$ levels, and that the relationship between etCO$_2$ and VCO$_2$ is contingent on alveolar ventilation which could have differed between the respective samples. VCO$_2$ is the only capnographic measure that demonstrated medium to large effect sizes and was sensitive to increasing task difficulty which suggests that mental effort actually entails additional energy expenditure (see also Backs & Seljos, 1994). PetCO$_2$ was less sensitive regarding the magnitude of changes and task difficulty. However, petCO$_2$ was consistently reported to decrease whereas findings on VCO$_2$ did not entirely point in the same direction. Since petCO$_2$ additionally provides information on whether ventilatory changes in response to mental load correspond to actual changes in metabolic demand, both petCO$_2$ and VCO$_2$ are promising indicators of mental load. Future studies should therefore validate and integrate the existing findings.

Only six studies analyzed respiratory changes over the course of the mental task or from trial to trial. For most variables, these studies revealed no change as well as inconsistent findings for the habituation of RR. Hence, changes in respiratory reactivity over time also require further investigation.

*Methodological evaluation*

By specifying a priori selection criteria we obtained a database of experimental studies on mental load with an acceptable degree of consistency regarding study design and the induction of operator load. Although performance feedback during mental tasks has been assumed to elicit stress responses comparable to the effects of social evaluative threat (Cacioppo, Rourke, Marshall-Goodell, Tassinary, & Baron, 1990; Gaillard & Wientjes, 1994; Wright, Tunstall, Williams, Goodwin, & Harmon-Jones, 1995), we decided not to exclude these studies but to analyze them additionally in comparison with studies not providing feedback. Also, we did not exclude any study applying verbal-response tasks in order to maintain a sufficiently large sample of studies. Instead, we accepted studies with a limited amount of verbal activity and additionally evaluated them separately in a sub-analysis.

As summarized above, most of the studies manipulated mental load by means of mental arithmetic or multi-tasking. The 11 studies including more than one type of cognitive task in their experimental design (see Table A) imply that the magnitude of respiratory effects may vary depending on the given types of cognitive demands. Especially sigh rate and respiratory variability measures have been shown to be differently altered by mental arithmetic and attentional tasks (Novak, Mihelj, & Munih, 2012; Vlemincx et al., 2011; Vlemincx et al., 2012). However, the current database is insufficient for a systematic investigation of respiratory responses to various facets of cognition. Also the findings reported by Roman-Liu, Grabarek, Bartuzi, and Choromański (2013) suggest that vigilance behavior, involving uninterrupted attention on the detection of infrequent signals, is characterized by particular respiratory changes which should be addressed in future studies.

In a separate analysis, we investigated whether concurrent performance feedback affects respiratory responses to mental load. In general, the reviewed studies imply that performance feedback on cognitive tasks is only accompanied by a decrease in TV, which has not been observed in the overall findings outlined above. Since decreases in TV have also been reported for negative emotions such as anxiety and sadness (Kreibig, 2010), we conclude that a concurrent feedback may have emotional impact on the operator, inducing rather stress than mental load (see also Gaillard & Wientjes, 1994; Jerusalem & Schwarzer, 1992; Light & Obrist, 1980), and should thus be avoided in future experiments on mental load. Unfortunately, no data were available to evaluate the effect of performance feedback on variability measures.

Our survey revealed that most of the studies used recording techniques that are not directly disturbed by speech. But since respiration itself may be affected by verbal activity, we additionally reviewed the seven studies involving speech. In sum, the findings were inconsistent and generally corresponded to the overall effects. However, the systematic comparison of verbal- and manual-response conditions also revealed some indication for erratic breathing patterns as well as shorter inspiration and longer expiration phases when performing a mental arithmetic with verbal responding. Given that this is in line with the existing knowledge of the interplay of speech and respiration (Conrad & Schönle, 1979; Winkworth et al., 1994) and that manual responding is easy to integrate in computerized task designs, we suggest to evaluate respiratory measures for the assessment of operator load only under silent conditions.

### *Limitations*

The findings of this review should be interpreted with regard to several limitations. First, our analyses were restricted to published journal articles and we found some indication for publication bias, meaning that analyses on respiratory parameters with insignificant results were reported less often. For instance, some studies described the measurement of single variables without mentioning the according results. As displayed by the integration of reactivity effects, however, a considerable number of studies also reported respiratory measures showing no changes from baseline to task. Second, only 50% of the reviewed studies provided data for a determination of respective effect sizes. Third, the present integration of findings was not weighted according to sample size and quality criteria as required for the statistical data integration in meta-analyses, since larger samples are supposed to increase the precision of findings (Lipsey & Wilson, 2001; Moher et al., 2009). This choice was made because the magnitude of effects could be quantified only in 50% of the studies, suggesting a qualitative comparison. But we followed the recommendations by Durlak (2009) to adjust the obtained effect sizes for small sample bias. Fourth, comparability of the reviewed studies is limited due to heterogeneous study samples and possible differences regarding the motivation of participants (experimental context, instructions, incentives) and study design (randomization of trials with modified task difficulty). Fifth, only a small number of studies mentioned to have included potential confounders (covariates) in their analyses such as age, what possibly could lead to an over- or underestimation of effects. Finally, except for RR, TV, and MV, only few studies were available reporting data for addressing the present research question. As a consequence, it was not possible to investigate whether respiratory responses vary as a function of different types of cognitive processing.

*Conclusive summary and implications for a research agenda*

The primary aim of this study was to investigate whether respiratory parameters are useful indicators of mental load in addition to other physiological correlates and well-established performance and self-report measures. We found evidence that RR is a sensitive measure of operator load which can be obtained easily and inexpensively by using a strain gauge. While at first sight TV and MV may contain little additional information, correlated variability in RR, sigh frequency, $petCO_2$, $VO_2$, and $VCO_2$ are promising measures for research and application purposes as they appear to be sensitive to mental load and, furthermore, reflect some of the physiological and psychological processes underlying task-related changes in respiratory behavior. However, this review also revealed that the database for evaluating these measures is rather poor in quantity and quality and that most studies are restricted to the traditional measurement of RR and TV.

Since a further motive underlying this study was to contribute to the relatively limited knowledge about breathing under mental load, we derived some general recommendations for future research as based on a proper understanding of the respiratory system. The respiratory apparatus is a complex, multilayered, integrated, and highly versatile system serving to maintain appropriate partial pressures of $O_2$ and $CO_2$ in the blood to accommodate both metabolic and behavioral demands. At the same time, respiration is intricately involved in speech production. Breathing regulation hence serves stability but also allows flexibility to quickly adapt to internal and external homeostatic challenges. The respiratory system at rest is considered a dynamic steady state that is characterized by different types of variability and occasionally requires “resetting” which apparently is accomplished by sighing (Vlemincx, Abelson, Lehrer, Davenport, Van Diest, & Van den Bergh, 2013). Importantly, breathing is also largely driven by feedforward regulation, meaning that the system anticipates perturbations (i.e., discrepancies from normative values) and corrects them before they occur (Zaman et al., 2014; Gallego, Nsegbe, & Durand, 2001).

This perspective has a number of implications for the use of respiration to assess mental load. First, baseline recordings during which an episode of mental load is anticipated may already show its influence and reduce possible effects of the mental load manipulation. This problem could be solved by a randomization of baseline and task conditions and by including a "Vanilla baseline" with a low demanding mental task, occupying working memory and thus reducing anticipatory arousal (Jennings et al., 1992).

Second, RR alone provides only very partial information about the dynamic changes of the respiratory system. Underlying drive and timing mechanisms such as central inspiratory drive and inspiratory duty cycle may be much more sensitive to mental and emotional demands (Van Diest, Janssens, Bogaerts, Fannes, Davenport, & Van den Bergh, 2009). Moreover, RR alone does not signal whether ventilatory response is adaptive or maladaptive. An increase in rate may be adjusted by a decrease in TV to maintain appropriate breathing. However, absence of appropriate compensation by TV may result in overbreathing, which results in a decrease in $etCO_2$. As a consequence, the combined assessment of RR, MV (the product of RR and TV), and gas exchange parameters, particularly $etCO_2$, provide a more integrated account of respiratory responses to mental load. An additional benefit is that $etCO_2$ allows to assess whether the response to mental load is in accordance with or in excess of metabolic requirements. The latter state (hypocapnia) is of particular relevance for mental load because hypocapnia is associated with reduced cerebral blood flow and possibly impaired cognitive performance (Matthews et al., 2010; Van den Bergh, Zaman, Bresseleers, Verhamme, & Van Diest, 2013; Van Diest et al., 2000). In this respect, a more integrated assessment may help to distinguish between mental load and stress. In the first case, respiratory changes are supposed to be task-related and support adequate performance, while in the latter case – stress being linked with concerns about threats and protection of the self – respiratory changes may exceed task-related metabolic need (Suess, Alexander, Smith, Sweeney, & Marion, 1980; Wientjes et al., 1996).

Third, recent evidence suggests that general and specific parameters of respiratory variability allow measuring stability and flexibility of the respiratory system in response to mental load (Vlemincx, Abelson, Lehrer, Davenport, Van Diest, & Van den Bergh, 2013; Vlemincx, Van Diest, & Van den Bergh, 2015). Specifically, variability in RR has been shown to decrease during sustained attention as induced by a task with a single behavioral response set, while decreased autocorrelations and increased random variability in respiration have been found during mental arithmetics (Vlemincx et al., 2011, 2012). Moreover, the need of the respiratory system to reset has been found to differ between sustained attention and mental arithmetic, as manifested by a higher frequency of sighing during or after the task, respectively (Vlemincx et al., 2011). These findings suggest that variability in the respiratory system is sensitive to different types of mental load and that it is useful to decompose the concept of mental load into basic components. A systematic approach to basic mental processes might also clarify current inconsistencies in respiratory correlates of mental load as revealed, for instance, by this review. To this end, elementary cognitive tasks which require a small number of cognitive processes such as joystick tracking, card-sorting, or response choice tasks could be used in single as well as multiple task configurations, manipulated at different levels of task difficulty to study respiration in response to increasing mental load (see also Carroll, 1995).

Fourth, we suggest to take individual differences into account. Emotional states and personality traits may play an important role in how a demanding cognitive task is appraised, how coping resources are evaluated, and how the individual responds (Carroll, 1978; Grassmann, Vlemincx, von Leupoldt, & Van den Bergh, submitted; Masaoka & Homma, 1997, 1999; Stemmler & Wacker, 2010). Specific combinations of individual and task-related characteristics may elicit different respiratory patterns, possibly ranging from a strained breathing pattern (characterized by breathing inhibition with elevated $etCO_2$) when preparing for highly attentive episodes (Fokkema, 1999) to hypocapnic hyperventilation when preparing to cope with demanding situations by energy mobilization (Grossman & Wientjes, 2001; Van Diest et al., 2001). A comprehensive assessment, involving the interaction of physiological and person-related measures, is hence required for a better understanding of individual differences in the physiological response to mental load.

Finally, an integrative assessment of respiratory measures would be enriched by simultaneously taking cardiac measures into account because the respiratory system exerts considerable influence on cardiac functioning (Grossman & Taylor, 2007; Rosenblum, Cimponeriu, Bezerianos, Patzak, & Mrowka, 2002). Certainly, cardiac measures have a long tradition in mental load assessments which recently focused predominantly on heart rate variability (HRV). However, beyond studying respiratory sinus arrhythmia (being a major source of HRV; see Angelone & Coulter, 1964), concurrent respiratory assessments have largely been neglected. Although the debate on the usefulness of correcting for respiration when assessing HRV has not yet resulted in clear conclusions (see Berntson et al., 1997; Denver, Reed, & Porges, 2007; Grossman, Karemaker, & Wieling, 1991; Lewis, Furman, McCool, & Porges, 2012; Veltman & Gaillard, 1996), an integrated approach would provide a more elaborate database to detect and interpret psychophysiological responses to mental load. Obviously, the parallel assessment of cardiac and respiratory parameters would also impact data-analytic strategies. Analyses could be performed by applying classical multivariate statistics (if assumptions are met) or, for a more detailed examination, by time series data analysis such as change point detection methods (e.g., Bulteel et al., 2014), transfer function analysis (e.g., Faes, Porta, Cucino, Cerutti, Antolini, & Nollo, 2004), or similar methods that have been employed to study the structure of cardiorespiratory coupling (Galletly & Larsen, 1999; Mrowka, Patzak, & Rosenblum, 2000; Zhu, Hsieh, Dhingra, Dick, Jacono, & Galán, 2013).

# 5 The role of respiratory measures to assess mental load in pilot selection

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## 5.1 Abstract

Whereas cardiovascular measures have a long tradition of being used to determine operator load, responsiveness of the respiratory system to mental load has rarely been investigated. In the present study we assessed basic and variability measures of respiratory rate, partial pressure of end-tidal carbon dioxide (pet$CO_2$) as well as performance measures in 63 male pilot candidates during completion of a complex cognitive task and subsequent recovery. Mental load was associated with an increase in respiratory rate and a decrease in respiratory variability. A significant decrease was also found for pet$CO_2$. Respiratory rate and respiratory variability showed partial and complete effects of recovery, respectively, whereas pet$CO_2$ did not return to baseline level. Overall, a good performance was related to a stronger reactivity in respiratory rate. Our findings suggest that respiratory parameters would be a useful supplement to common measures for the assessment of mental load in pilot selection.

## 5.2 Introduction

The quantification of operator workload is an important objective in working environments that are characterized by high task demands and responsibility. Especially in the fields of aviation, space flight, military, and surgery, operational personnel are regularly faced with decision making under time pressure and stress (e.g., Morris & Leung, 2006). The aerospace sector has a long tradition of profound aptitude testing to ensure the fit between future operator and environment (Goeters et al., 2004; Harris, 2011). Since technical developments, however, involve constantly changing task demands impacting cognitive requirements, international airlines still seek to improve the assessment of mental load for the selection of pilots.

The construct of mental load has been defined as the ratio between task demands and operator capacity (e.g., Gopher & Donchin, 1986; Kantowitz, 1987; O'Donnell & Eggemeier, 1986). Since human processing resources are limited, the level of mental load is influenced by difficulty and complexity of the task as well as by the individual's skills, abilities, and motivation. Methods to measure mental load are generally classified on the basis of performance, self-report, and psychophysiological assessment which are supposed to reflect different aspects of mental load (see Young, Brookhuis, Wickens, & Hancock, 2014). While performance-based and self-report measures are generally easier and cheaper to use, psychophysiological parameters are more cumbersome but also have some advantages over the former measures. First, they contain information about the "physiological costs" that are related to the effort being invested to accomplish the task. In contrast to performance measures, this also allows analysts to draw conclusions about the operator's remaining capacity. Second, physiological parameters can be assessed and monitored continuously while self-reports are usually retrospective. Third, physiological measures are not distorted by memory lapse or observer bias. Especially in personnel selection, where the tendency to present oneself in a favorable light poses a diagnostic problem, the usefulness of self-reports is limited.

Whereas cardiac measures have been studied extensively as a workload index in the field of aviation (e.g., Jorna, 1993; Roscoe, 1993; Svensson, Angelborg-Thanderz, Sjöberg, & Olsson, 1997; Wilson, 2002), little research has been devoted to respiratory measures. The main reasons are probably that such measurements are more complicated because of the artefacts, which may be caused by speech and movement, as well as the fact that measurement devices assessing tidal volume are rather obtrusive. Another reason might be that respiration is in part under conscious voluntary control, while psychophysiological measures are often used because they are considered "objective" measures, reflecting autonomic regulation mechanisms that are inaccessible to volitional control. Grossman and Wientjes (2001, p. 43) suppose, however, that "respiratory adjustments to highly specific behavioral demands have evolved as functional integrative adaptions to best fit and coordinate metabolic activity, cognitive performance, emotional self-regulation and perhaps even communicative signaling to conspecifics". Awareness and conscious responsiveness of respiration are therefore crucial arguments to study the effects that psychological processes might have on the respiratory system.

The regulation of respiration is based on an interaction of the autonomic nervous system and respiratory centers in the medulla oblongata and pons on the one hand and the limbic system, cerebellum, and higher cortical areas, which can affect central breathing reflexes, on the other hand. Hence, the respiratory pattern is contingent upon metabolic and homeostatic influences but also responds to cognitive and emotional processes. In contrast to the investigation of emotional influences on basic respiratory measures such as rate and volume (e.g., Bloch, Lemeignan, & Aguilera-T., 1991; Boiten, 1998; Boiten et al., 1994; Gomez, Stahe, & Danuser, 2004) and on variability measures of respiration (e.g., Boiten, 1998; Van Diest, Thayer, Vandeputte, Van de Woestijne, & Van den Bergh, 2006; Vlemincx, Vigo, Vansteenwegen, Van den Bergh, & Van Diest, 2013), there is only little research on the effects of mental load on human respiratory behavior.

Respiratory rate, or total breath duration, is the measure being used most frequently in respiratory reactivity research and regarded as one of the most sensitive measures of mental load (Backs, Ryan, & Wilson 1994; Brookings et al., 1996; Pattyn et al., 2010). Studies investigating task-related changes in respiratory rate consistently show that participants breathe faster when performing a mentally demanding task both in the laboratory (Allen & Crowell, 1989; Boiten, 1998; Brookings et al., 1996; Mehler, Reimer, Coughlin, & Dusek, 2009; Pattyn et al., 2010; Van Diest et al., 1999; Veltman & Gaillard, 1998; Vlemincx et al., 2011; Vlemincx et al., 2012; Wientjes et al., 1998) and in real-life settings (Harding, 1987; Karavidas et al., 2010; Pattyn et al., 2010; Veltman, 2002; Wilson, 1993).

The analysis of respiratory variability is a promising, yet rarely applied method to investigate the psychophysiology of mental load (Vlemincx et al., 2011; Vlemincx et al., 2012; Wientjes, 1992). Respiratory variability can be described as the breath-to-breath variation of spontaneous breathing and potentially reveals information about the appropriateness of respiratory control mechanisms (Tobin, Mador, Guenther, Lodato, & Sackner, 1988). Instead of analyzing only total variability in respiratory signals, Vlemincx, Van Diest, Lehrer, Aubert, and Van den Bergh (2010) suggested to distinguish between different components of variability, a structured or correlated component and a random component. While external influences such as cognitive and emotional demands may cause an increase in random variability, internal homeostatic regulation would cause an increase in correlated variability in order to stabilize the system. The effects of mental load on these different variability components have been investigated by means of a mental arithmetic task (Vlemincx et al., 2011). It was shown that mental load was accompanied by an increase in total variability but a decrease in correlated variability in respiratory rate, suggesting an increase in the random fraction. However, in a low demanding sustained attention task, both total variability and correlated variability in respiratory rate were reduced (Kagan & Rosman, 1964; Vlemincx et al., 2011; Vlemincx et al., 2012). This suggests that total and correlated variability are highly sensitive to mental load, possibly differentiating between distinct cognitive processes that occur during the performance of different types of tasks.

Another respiratory measure that provides information about the fit between ventilation and metabolic demands is end-tidal carbon dioxide (et$CO_2$). The partial pressure of et$CO_2$ (pet$CO_2$) is highly correlated with alveolar p$CO_2$ (Wientjes, 1992) which, in turn, is regarded as a valid estimate of arterial p$CO_2$ (Phan et al., 1987; Takano et al., 2003). Given that p$CO_2$ decreases if ventilation exceeds metabolic demands (hyperventilation) and that respiratory behavior is sensitive to psychological influences, it seems reasonable to investigate pet$CO_2$ as a possible measure indicating over-activation in response to mental load. Wientjes et al. (1998) report a significant but small decrease in pet$CO_2$ during the performance of a memory task, which is in line with other studies that investigated end-tidal and transcutaneous p$CO_2$ levels in response to highly demanding aviation settings (Harding, 1987; Wientjes et al., 1996). This measure is particularly important because it has been shown that inappropriate changes in respiratory rate and depth, inducing hypocapnia, may reduce oxygen supply to the brain and that brain oxygenation appears to be associated with impaired cognitive performance (Gibson, 1978; Matthews et al., 2010; McCarthy, Corban, Legg, & Faris, 1995; Van Diest et al., 2000). While these relationships are well established for substantial hypocapnic overbreathing, here defined as $petCO_2 < 32$ mmHg, there is little research on the covariation of task performance with less dramatically reduced $petCO_2$ levels.

Whereas inappropriate physiological arousal as indicated, for instance, by hyperventilation might impair cognitive performance, appropriate physiological arousal in response to mental load is assumed to be beneficial (Andreassi, 1966; Dienstbier, 1989; Jennings & Wood, 1977; Lacey, 1967; Obrist et al., 1974). As described by Dienstbier (1989), a low base rate of arousal, a strong sympathetic response to challenge involving release of adrenaline and noradrenaline, and a quick decline of arousal after a challenge are not only associated with superior mental and physical health but also with better cognitive performance. A quick and efficient adaption to onset and offset of a demanding task indicates psychological and physiological flexibility, which generally reflects a healthy state of the individual (Kashdan & Rottenberg, 2010). Flexibility is hence considered a prerequisite for the organism to properly regulate physiological arousal and to ensure optimum performance. For cardiac variability, this rationale has been supported by empirical evidence (Hansen et al., 2003; Thayer, Hansen, Saus-Rose, & Johnsen, 2009).

The purpose of this study was to evaluate the sensitivity of respiratory parameters to mental load and to investigate whether task-related respiratory changes are associated with cognitive performance. In order to test this, we assessed respiratory rate, variability in respiratory rate, and $petCO_2$ during a baseline period, the performance of a highly demanding cognitive multiple task, reflecting the multi-tasking demands of airline pilots, and a recovery period. We expected that respiratory rate would increase from baseline to performance on the task and decrease during recovery. The total variability in respiratory rate was expected to be higher, whereas the correlated fraction was expected to be suppressed while performing the multiple task. For $petCO_2$ we hypothesized a decrease from baseline to task and an increase during recovery. It was expected that individuals with an appropriate respiratory behavior would perform better than individuals whose breathing pattern is not in line with metabolic demands.

## 5.3 Methods

*Participants*

The experiment was conducted at the German Aerospace Center where pilot selection is carried out on behalf of civilian airlines. 63 male volunteers were recruited from applicants who had been accepted for the selection procedure. The period of data acquisition corresponded with the ongoing selection period. In order to gain adequate power, a priori power analyses suggested a minimum of 56 participants. We continued data collection until that minimal number was surpassed. Candidates had to be fluent in German and hold a secondary-school diploma. Applicants suffering from acute illness, cardiovascular and respiratory disease, or any major psychiatric disorder were not allowed to participate. They further had to be non-smokers and refrain from stimulants such as caffeine prior to their experimental testing. The data sets from two participants had to be excluded because of movement artefacts. The resulting sample consisted of 61 participants with an age range of 18 to 43 years (*M* = 21.8, *SD* = 4.2). All participants gave their written informed consent prior to the experiment and obtained 25 € for participation.

*Procedure and experimental material*

Experimental sessions were run around 5 pm, subsequent to the regular pilot selection tests. Participants were seated in front of a computer screen, equipped with physiological recording devices and asked to complete a questionnaire covering their age, dominant hand, regular physical activity, and body mass index (BMI). After 10 to 15 minutes of signal stabilization, subjects started to go through the entire experimental protocol being guided by written instructions on a touch screen. All participants had to use their right hand to interact with the display.

The experimental protocol consisted of a six-minute resting baseline, a six-minute vanilla baseline, a six-minute multiple task, and a six-minute recovery period, all of which were separated by a break of three minutes. During the resting baseline participants had to fix their eyes on a cross. A test instructor verified that participants kept their eyes focused on the monitor. The vanilla baseline was presented in addition to the resting baseline in order to reduce possible effects of anticipatory arousal with a minimally demanding vigilance task (Jennings et al., 1992). Since the presented vigilance task, however, was not accompanied by lower respiratory levels than the resting baseline, only resting baseline data were used for the statistical analysis of baseline-to-task changes. To induce mental load in a way that is similar to the cockpit workload of a civilian aircraft, a highly demanding multiple task was chosen which consisted of three single tasks measuring perceptual speed, spatial orientation, and working memory capacity, which had to be carried out in parallel. The perceptual speed task required the simultaneous scanning of four instruments. The pointer of each instrument indicated one of eight directions (Figure 1a). The task was to detect the number of instruments showing the same value. The spatial orientation task measured mental rotation and spatial processing ability. A pictogram of an aircraft was shown that could be rotated around its center, pointing in one of 12 directions (comparable to a clock face). In addition, a spot was shown in one of the 12 positions on an imaginary circle around the aircraft (Figure 1b). Participants had to indicate the spot’s position (clockwise 1–12) relative to the center and flight direction of the aircraft. The working memory task required memorizing pairs of colors (grey, blue, brown, green) and two-digit numbers that were presented acoustically (e.g., “green two eight”). A two-digit number was displayed on the screen (Figure 1c), continuously increasing from 13 to 99. The number changed every four seconds. As soon as one of the acoustically given numbers appeared on the screen, subjects had to click on the corresponding color button. In the given example, the green button would have to be activated as soon as “28” appeared on the screen. The pairs of color and number were generated in a controlled randomized way to assure a constant level of task difficulty. A new pair of colors and numbers was given every four seconds; the delay between acoustic and visual stimulus varied systematically between 12 and 24 seconds. The maximum number of pairs that had to be remembered simultaneously was four. Prior to the multiple task (Figure 2), participants were instructed to allocate their attention evenly to the three tasks and to work as fast and accurately as possible. During the recovery period, participants listened to relaxing music and watched an aquatic movie.

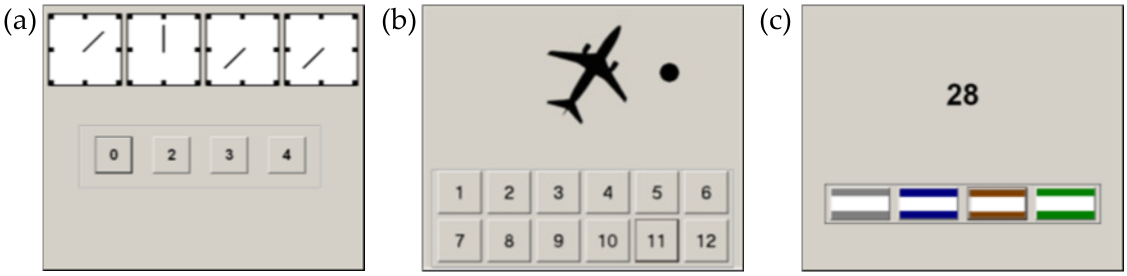

Figure 1. Exemplary items and corresponding keypads of the (a) perceptual speed task (correct response: "2"), (b) spatial orientation task (correct response: "2"), and (c) working memory task.

To avoid artefacts caused by speech and movement, participants were instructed not to talk during data acquisition and to avoid any movement apart from using their right hand to operate on the touch screen. Actual movement activity was controlled by an accelerometer which was fixed to the thorax and visually monitored by the experimenter.

*Performance measures*

Two types of performance measures were applied: first, task performance on the experimental multiple task and second, outcome of the regular cognitive aptitude exam that was administered in the pilot selection protocol by the German Aerospace Center. Given that this test protocol covers basic mental abilities such as working memory, spatial orientation, psychomotor coordination, and multi-tasking, the outcome measure is regarded as being comparable to the experimental task measure.

The performance score of the multiple task was obtained by multiplying the total number of correct responses to the three single tasks after z-standardization (i.e., sum scores were standardized across subjects within each single task). Performance data from three participants were missing due to technical problems. The dichotomous outcome measure from the cognitive aptitude exam (pass/fail) was obtained by applying the decision rules which are used for pilot selection: Raw scores from the different test domains (e.g., working memory, spatial orientation, psychomotor coordination and multi-tasking abilities) were each normalized by means of a stanine transformation. Stanine scores range from 1 (low performance) to 9 (high performance) with a mean of 5 and a standard deviation of 2. If the resulting stanine scores were greater than or equal to 4 for each ability domain being tested, the cognitive aptitude exam was regarded as "passed".

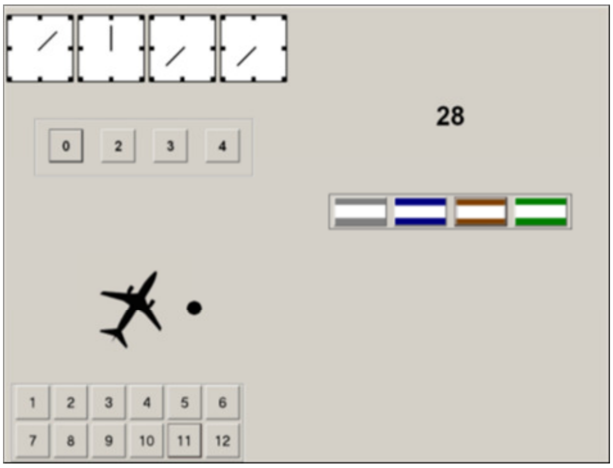

Figure 2. Screenshot of the multiple task.

*Physiological measures*

Respiratory rate (RR) and $pCO_2$ were measured using a mainstream capnograph (Nihon Kohden Europe GmbH, Rosbach, v.d.H.) which analyses the expired air with a lightweight infrared sensor that is placed unobtrusively between nostrils and upper lip. Participants were instructed not to speak and to breathe only through their nose during the experimental periods. Respiratory data were sampled continuously at 20 Hz as well as breath-by-breath. RR was exported directly from the breath-by-breath records. The ANSLAB software (Wilhelm & Peyk, 2005) was used to derive end-tidal plateau values ($petCO_2$) from the continuous $pCO_2$ records for each individual and period. Outliers (± 2 *SD*) detected within one data record were corrected by linear interpolation after visual inspection.[9] Variability in RR was quantified by two types of measurement, the coefficient of variation (CV) and autocorrelation (AR). CV indicates total variability in RR within one record, whereas AR indicates the structured, correlated fraction of variability (Tobin,

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[9] Altogether, 5% of the 18 971 plateau values were interpolated. We confirmed our reported findings by reanalyzing the $petCO_2$ data including outliers.

Yang, Jubran, & Lodato, 1995). AR coefficients reported here indicate the correlation between one breath and the following one.

Prior to data analysis, the first and last 30 seconds of the six-minute data records of each experimental period were cut in order to avoid artefacts that sometimes occurred at the beginning or end of a period and to obtain stationary data which is required for the computation of AR coefficients.[10] Mean scores and variability measures were hence computed on the basis of five-minute records. Reactivity scores were obtained by calculating the difference between the mean scores of the baseline and the task period.

*Statistical analysis*

All analyses were performed using SPSS 21.0 for Windows (SPSS Inc., Chicago, IL). To evaluate psychophysiological changes in response to mental load, respiratory variables were subjected to a repeated-measures multivariate analysis of variance (MANOVA) using Pillai's trace with period (baseline/vanilla baseline/multiple task/recovery) as a within-subject variable. Greenhouse-Geisser corrections were applied in the following ANOVAs if the assumption of sphericity was not met. If multivariate and univariate statistics were significant, experimental periods were compared post-hoc using Bonferroni-corrected *t*-tests. Bivariate associations between respiratory measures and multiple task performance were assessed via Pearson's correlation. To analyze relationships with the outcome of the cognitive aptitude exam, respiratory measures were each subjected to a two-way repeated-measures ANOVA with period (baseline/vanilla baseline/multiple task/recovery) as a within- and outcome (pass/fail) as a between-subject variable. Greenhouse-Geisser corrections were applied if necessary.

We defined the family-wise alpha level as 0.05 and corrected for multiple comparisons using the Holm-Bonferroni method (Aickin & Gensler, 1996; Holm, 1979). Control variables (age, regular physical activity, BMI) were not included in the final analyses

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[10] For validation purposes, all analyses were rerun without cutting the first 30 seconds. These additional findings replicated our initial results showing that the truncated periods did not leave out crucial information.

because they did not covary with the dependent variables. Post-hoc power analyses using GPower 3.1 confirmed that our statistical analyses were sufficiently powered (Faul, Erdfelder, Lang, & Buchner, 2007).

## 5.4 Results

*Respiratory measures and mental load*

The MANOVA revealed a significant effect of period on RR, CV, AR, and petCO$_2$ ($V$ = 0.82, $F(12, 49) = 18.92$, $p < .001$). Univariate statistics are reported in Table 3. RR increased from baseline to task ($p < .001$) and decreased after the task ($p < .001$) but without going back to baseline level ($p < .001$). For CV and AR, we found a significant decrease from baseline to task and a significant increase from task to recovery period. Changes in CV were significant at a level of $p < .001$ from baseline to task and at $p < .01$ from task to recovery. Changes in AR were significant from baseline to task ($p < .05$) and from task to recovery ($p < .001$), reaching a higher level than during baseline ($p < .05$). PetCO$_2$ decreased significantly from baseline to task ($p < .05$) and did not recover after the task when comparing to baseline level (n.s.). Hypocapnic hyperventilation during task performance, defined as petCO$_2$ < 32 mmHg, was found in three participants. In 25% of the sample we obtained petCO$_2$ levels of 34.43 mmHg or lower.

*Respiratory measures and performance*

Correlation analysis showed that a better performance on the experimental task was associated with lower RR during baseline ($r = -.33$, $p < .05$) and stronger reactivity in RR ($r = .34$, $p < .01$). A better task performance was also associated with higher AR during baseline ($r = .37$, $p < .01$). After excluding two outliers in the multiple task performance score (± 3 *SD*), resulting correlations were non-significant for RR during baseline and weaker for reactivity in RR ($r = .28$, $p < .05$) as well as for AR at baseline ($r = .30$, $p < .05$). Analyses of the relationship between respiratory measures and the outcome of the cognitive aptitude exam showed a significant interaction between experimental period and outcome of the exam for respiratory rate ($F(2.19, 129.06) = 6.37$, $p < .01$, $\eta_p^2 = .10$). As depicted in Figure 3, applicants who passed the regular aptitude tests ($n = 20$) showed a higher reactivity from baseline to task and also a faster recovery after the task than those applicants who failed (*n* = 41).[11]

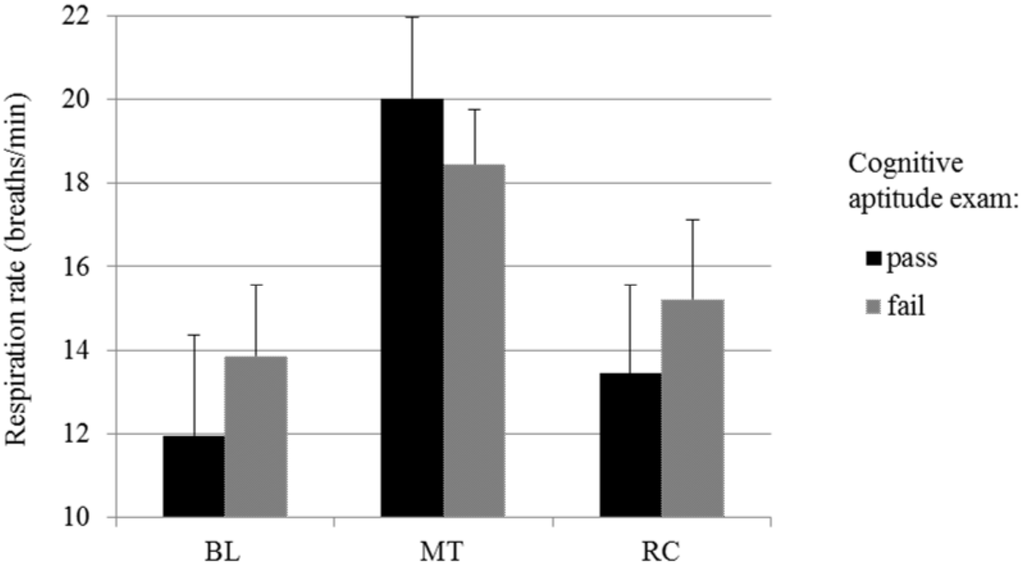

Figure 3. Mean respiratory rate during baseline, multiple task and recovery for participants who passed (*n* = 20) and participants who failed (*n* = 41) the cognitive aptitude exam for pilot selection. Error bars indicate standard deviations.

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[11] The dichotomous variable "outcome of the cognitive aptitude exam" was composed of nine different test domains (see above). To validate these findings, we reanalyzed our data using the stanine scores of those four test domains that are conceptually related to the experimental multiple task (i.e., working memory, spatial orientation, perception/concentration, and multi-tasking abilities). In line with the reported results, we found significant positive correlations between performance stanine scores and the increase in RR from baseline to task, on the one hand (working memory: $r = .39$, $p < .01$; spatial orientation: $r = .36$, $p < .01$; perception/concentration: $r = .32$, $p < .05$; multi-tasking abilities: $r = .30$, $p < .05$), and the decrease in RR from task to recovery period, on the other hand (working memory: $r = .39$, $p < .01$; spatial orientation: $r = .38$, $p < .01$; perception/concentration: $r = .26$, $p < .05$; multi-tasking abilities: $r = .44$, $p < .001$).

Table 3. Means (*M*), standard deviations (*SD*), and repeated-measures ANOVA results (including effect size $\eta_p^2$) for basic and variability respiratory parameters.

| | | BL | | V-BL | | MT | | RC | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *N* | *M* | *SD* | *M* | *SD* | *M* | *SD* | *M* | *SD* | df | df$_{error}$ | *F* | *p* | $\eta_p^2$ |
| RR | 61 | $13.24^{a}$ | 3.95 | $14.90^{b}$ | 3.65 | $18.96^{c}$ | 3.15 | $14.64^{b}$ | 4.00 | 2.05 | 123.02 | 80.91 | <.001 | .57 |
| CV (RR) | 61 | $.19^{a}$ | .09 | $.17^{a}$ | .07 | $.13^{b}$ | .05 | $.19^{a}$ | .13 | 2.49 | 149.33 | 12.71 | <.001 | .18 |
| AR (RR) | 61 | $.13^{a}$ | .17 | $.14^{a}$ | .16 | $.05^{b}$ | .11 | $.21^{a}$ | .16 | 3 | 180 | 12.48 | <.001 | .17 |
| petCO$_2$ | 61 | $36.80^{a}$ | 2.98 | $36.59^{a}$ | 2.70 | $36.06^{b}$ | 2.75 | $35.72^{c}$ | 3.02 | 2.26 | 135.70 | 12.56 | <.001 | .17 |

*Note*. RR: respiratory rate, CV: coefficient of variation, AR: autocorrelation, petCO$_2$: partial pressure of end-tidal carbon dioxide, BL: baseline, V-BL: vanilla baseline, MT: multiple task, RC: recovery.

$^{a, b, c}$ Different letters in the same row indicate significant differences ($p < .05$).

## 5.5 Discussion

In line with our hypothesis and prior studies, respiratory rate strongly increased during the performance of a difficult multiple task and decreased during the subsequent recovery period. However, respiratory rate did not fully reach baseline level within the recovery time. The high sensitivity of respiratory rate, as indicated by a strong effect size ($\eta_p^2 = .57$), replicates the findings reported in earlier work but using a multiple task that is comparable to the work demands of airline pilots. Our data hence further support the usefulness of respiratory rate for the measurement of operator load in aviation. That respiratory rate was not completely restored raised the question whether the given time window was too short in the present study. For recovery from a mental arithmetic, however, it has been shown that five to six minutes seem to be sufficient for a full return to baseline breathing frequency (Vlemincx et al., 2011). In contrast to the consistent findings on the reactivity of respiratory rate to mental load, the mechanisms of recovery are poorly understood and require further investigation.

Both total and correlated variability in respiratory rate were suppressed by the induction of mental load which indicates that respiratory flexibility was reduced during the task period. While a lower correlated variability is in line with existing research (Vlemincx et al., 2011; Vlemincx et al., 2012), the finding that total variability was also reduced contradicts the results reported by Vlemincx et al. (2011) for a mental arithmetic. As outlined above, a reduction in total variability has previously only been reported for sustained attention (Kagan & Rosman, 1964; Vlemincx et al., 2011; Vlemincx et al., 2012). The mental task that was applied in the present experiment, however, can be characterized as attentionally highly demanding as it required allocating the necessary processing resources to the different task components. Multiple tasks, which are more appropriate when studying psychophysiological correlates of operator load in working situations that are characterized by multi-tasking, can therefore not be compared to single task tests that have been used in the mentioned studies on respiratory variability. After having finished the task, total variability returned to baseline level and correlated variability was even higher than during baseline, revealing that respiratory flexibility was fully restored within the given recovery period. The finding that the correlated fraction was higher during recovery than during baseline implies that the anticipation of an unknown multiple task might have caused an increase in random variability already during baseline. Taken together, multi-tasking – which is an important requirement in the field of aviation – appears to affect respiratory variability in a different way than single tasks.

Pet$CO_2$, which can be regarded as an indicator of breathing in accordance with metabolic needs, decreased significantly during task performance but only to a moderate extent. A modest but continuous hyperventilation was also reported for mental performance in the laboratory (Wientjes et al., 1998) as well as during difficult flight maneuvers (Harding, 1987) and stressful air traffic control tasks (Wientjes et al., 1996) in the field. The fact that pet$CO_2$ reached clinically relevant levels in a small subset of participants suggests that this measure might be particularly important in order to detect individuals with a tendency to hypocapnic overbreathing, hence overreacting in highly demanding situations. Interestingly, we observed a prolonged overbreathing in this sample such that pet$CO_2$ did not recover after task completion while respiratory rate did show clear effects of recovery. This implies that tidal volume, which was not assessed in the present study, remained at a high level. In a study investigating the recovery from voluntary hyperventilation, Wilhelm, Gerlach, and Roth (2001) report detailed findings on the course of pet$CO_2$ recovery across a period of 10 minutes showing that the physiological readjustment of pet$CO_2$ still continues after 6 minutes. In addition, tidal volume returned to baseline level within that recovery period why a time span of 10 minutes appears to be more appropriate than shorter periods to assess complete respiratory recovery.

Analyzing whether respiratory behavior is related to operator performance was a further aim of this study. The fact that three participants of the present sample responded with hypocapnic hyperventilation demonstrates that a laboratory cognitive task possibly can lead to $CO_2$ levels which might affect cognitive performance. An investigation of pet$CO_2$ during simulated flight maneuvers by Karavidas et al. (2010) likewise suggests that task-induced hyperventilation might be associated with performance decrements. It can be assumed that mentally demanding situations with more impact (e.g., real-life situations) would probably lead to stronger effects which then, in turn, could impair brain oxygenation. In the present study we analyzed operator performance using the total performance score on the multiple task as well as the outcome of the candidates' cognitive aptitude exam that is applied in pilot selection. The analysis of respiratory rate and multiple task performance revealed that lower baseline values and a strong reactivity were associated with better performance scores. Even though the task-related decrease in $petCO_2$ reported above suggests that several participants showed a breathing response exceeding metabolic demands, the present finding argues that a strong increase in respiratory rate was appropriate to perform well. An explorative analysis of baseline measures revealed that correlated variability in respiratory rate at rest was also associated with a better performance on the multiple task which might imply that structured respiratory variability is beneficial for cognitive processing as it is required for multiple task performance. It has to be noted, however, that the correlation coefficients were moderate and have to be interpreted with caution. When using the outcome of the cognitive aptitude exam as a performance measure, we found that candidates who passed the exam had a lower respiratory rate at baseline, a stronger increase from baseline to task, and again a lower respiratory rate in the recovery period than candidates who failed. It could be argued that the actual exam performance might have influenced respiratory rate at baseline because the experiment was conducted subsequent to the aptitude testing. Even though the candidates did not receive any feedback on their exam performance, we additionally analyzed the relationship between outcome of the cognitive aptitude exam and performance on the experimental multiple task as well as respiratory variability during the experiment in order to investigate possible feedforward effects. Since none of the associations was significant in our sample, it can be assumed that respiratory behavior during the experiment was not affected by the outcome of the cognitive aptitude testing. The reported findings thus provide additional support for a positive relationship between reactivity in respiratory rate and cognitive performance. Certainly, the present data do not allow drawing conclusions about the latent variables that are responsible for the covariation of increased ventilation and enhanced cognitive performance. It remains for future research to determine the contributing psychological and physiological processes as, for instance, task engagement and brain oxygenation.

However, performance was not significantly related with $petCO_2$ what indicates that the amount of reactivity in $petCO_2$ being induced by the multiple task was too small to cause measurable effects on task performance. This interpretation is supported by previous studies suggesting that an impaired performance due to hyperventilation may occur only in individuals with a hypocapnic overbreathing response (Bloch-Salisbury et al., 2000; Gibson, 1978; Marangoni & Hurford, 1990; Van Diest et al., 2000). As mentioned before, with the exception of three participants this was not the case in the present sample. It is further remarkable that there is a strong between-subject variance in $petCO_2$. Because of the presence of hypocapnic episodes in three participants and the high interindividual variation, it might be suspected that some individuals experienced some kind of emotional stress in addition to the cognitive demands. Even though our experimental design was free of any emotional cue, the mere performance situation and presence of a test instructor can possibly elicit arousal responses (see also Sonderegger & Sauer, 2009).

In sum, our results replicate existing findings on the sensitivity of respiratory rate towards mental load by using a task that reflects the characteristic work environment of airline pilots and, furthermore, extend the small body of research on respiratory variability under mental load. Since respiration was not only related to mental load but also to cognitive performance, we conclude that respiratory measures contain valuable information for the assessment of mental load. Including these measures in pilot selection would provide a more comprehensive picture of operator state and hence improve the diagnostic process. Future studies should compare the different respiratory measures with cardiac and other well-established measures regarding both informational content and feasibility for the purpose of application. In pilot selection, it should further be discussed whether vulnerability to stress, as indicated by a tendency to hypocapnic overbreathing, might be used as an additional criterion. Moreover, our findings provide support that resulting changes in the breathing pattern reflect not only metabolic demands but also psychological processes. However, the differentiation of cognitive and emotional influences on respiratory regulation during task performance remains an important objective for future studies.

# 6 Individual differences in cardiorespiratory measures of mental workload

Based on: Grassmann, M., Vlemincx, E., von Leupoldt, A., & Van den Bergh, O. (submitted). Individual differences in cardiorespiratory measures of mental workload: An investigation of negative affectivity and cognitive avoidant coping in pilot candidates.

## 6.1 Abstract

Cardiorespiratory measures provide useful information in addition to well-established self-report measures when monitoring operator capacity. The purpose of our study was to refine the assessment of operator load by considering individual differences in personality and their associations with cardiorespiratory activation. Physiological and self-report measures were analyzed in 115 pilot candidates at rest and while performing a highly demanding multiple task. Whereas lower heart rate reactivity was observed in individuals characterized by avoidant coping, respiratory rate was reduced during task load and rest periods in individuals with higher levels of self-focused attention. Negative affectivity was not directly related to cardiorespiratory activation but moderated the association between cardiac and self-reported arousal measures. Given that physiological and self-report measures of mental workload are usually combined when evaluating operator load (e.g., in pilot selection and training), our findings suggest that an integration of individual differences may reduce unexplained variance and increase the validity of workload assessments.

## 6.2 Introduction

Many studies investigating the assessment of operator load have used physiological parameters as dependent measures in addition to self-report measures of mental workload (Cain, 2007; Lehrer et al., 2010; Miyake, 2001; Muth, Moss, Rosopa, Salley, & Walker, 2012; O’Donnell & Eggemeier, 1986). However, individuals differ in their physiological responses to an identical level of operator load just as they differ in respective self-reports. Some may perceive a task as threatening while others experience the same task as a challenge. Personality-related ways of coping with challenges and distress can therefore affect physiological activation (Carver & Scheier, 2011; Engel & Talan, 1991; Higgins, 2000; Stemmler & Wacker, 2010) and elicit different psychophysiological patterns in association with emotional and motivational states (Izard, Libero, Putnam, & Haynes, 1993; Mischel & Shoda, 1995). While interindividual variation in psychophysiology has been studied extensively in clinical, social, and health psychology, individual differences have little been addressed when studying the psychophysiology of mental workload in the field of human factors and ergonomics.

Szalma (2009), for example, argues for a consideration of motivational, emotional, and personality-related operator characteristics when investigating and developing human factors and ergonomics design methods, objecting against “the general trend […] to represent the human as a ‘black box’ of general cognitive mechanisms, while affective traits and states have been relatively neglected” (p. 382). Whether research is about human-machine interaction or, for instance, pilot selection and training, an incorporation of individual differences would reduce unexplained variance, which is usually treated as error or explained by possible variation in skill and ability.

Numerous studies have been devoted to the cardiac measurement of mental workload. Overall, mental workload has been found to increase heart rate during difficult tasks (Backs & Seljos, 1994; Boucsein et al., 2011; Fournier et al., 1999; Turner, 1989; Veltman & Gaillard, 1998) by affecting vagal and sympathetic pathways to the heart (e.g., Grossman et al., 1990; Porges & Byrne, 1992). The variation of interbeat intervals, also known as heart rate variability, has been reported to decrease in response to mental workload (Aasman et al., 1987; Backs & Seljos, 1994; Hansen et al., 2003; Mulder & Mulder, 1981; Vincente et al., 1987). However, a multitude of inconsistent findings exists that probably result from heterogeneous study designs and from neglecting the role of individual differences (Cain, 2007; Manzey, 1998).

Compared to cardiac parameters, respiration has rarely been investigated as a primary dependent measure in the assessment of operator load. Brookings et al. (1996), however, consider respiratory rate to be one of the most sensitive measures of mental task demands. In general, individuals breathe faster when executing complex tasks (Fournier et al., 1999; Lackner et al., 2010; Pattyn et al., 2010; Vlemincx et al., 2011; Wientjes et al., 1998; Wilson, 1993). Also variability in respiratory behavior (rate, minute ventilation) may be an interesting measure as it is thought to indicate the capability to flexibly adjust to environmental demands (Vlemincx, Abelson, Lehrer, Davenport, Van Diest, & Van den Bergh, 2013). For example, Vlemincx et al. (2012) report that, compared to baseline, sustained attention is characterized by a decrease in total variability in respiratory rate and that mental workload, as induced by a mental arithmetic task, is related to a decrease in correlated variability and an increase in total variability in respiratory rate. The partial pressure of carbon dioxide ($pCO_2$) indicates whether ventilation is appropriate to metabolic demands. Wientjes et al. (1998) report a significant but small decrease in $pCO_2$ from baseline to a difficult memory task. In the field of aviation, a few studies suggest that end-tidal and transcutaneous $pCO_2$ levels might be sensitive to workload changes related to characteristic job demands (Harding, 1987; Karavidas et al., 2010; Wientjes et al., 1996). However, individual differences have only infrequently been addressed in these studies.

In order to investigate between-subject variation in cardiorespiratory measures of operator load, we will focus on trait characteristics that are considered to play a role in cardiorespiratory arousal measures and that additionally show substantial variance in the target sample of the present study.[12] In a meta-analysis, neuroticism and trait anxiety have been reported in association with decreased cardiovascular reactivity to laboratory-induced stress but also with slower recovery (Chida & Hamer, 2008). Further recent reviews suggest neuroticism (Myrtek, 1998) as well as worry (Brosschot et al., 2006; Ottaviani et al., 2015) to be associated with slightly stronger cardiovascular arousal. Neurotic, anxious, and worried individuals have in common that they are more prone to experience negative emotions and rather concerned with negative cues than individuals with low negative affectivity.

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[12] Despite its theoretical relevance for emotional and physiological stress responses, the concept of self-esteem (Seery, 2011) was not included in this study because a pilot study (*N* = 102) revealed that pilot candidates showed insufficient variance and a leptokurtic distribution in self-esteem as measured by a revised version of the Rosenberg self-esteem scale (von Collani & Herzberg, 2003).

Among the very few studies that have investigated the relationship between personality traits and respiratory measures under mental workload and stress, Masaoka and Homma (1997, 1999) reported positive correlations between trait anxiety and respiration rate in response to mental stress. Trait anxiety has further been shown to covary with lower respiratory variability during anxious imagery (Van Diest, Thayer, Vandeputte, Van de Woestijne, & Van den Bergh, 2006), implying that the respiratory system is less flexible in anxious individuals. Whether negative affectivity accounts for interindividual variation in respiratory responses to mental workload thus requires further investigation.

The small to medium effect sizes, which are reported in the reviewing literature on cardiorespiratory reactivity, may be due to the combined analysis of different kinds of stressful situations while not considering individual differences in coping with stress. A cognitive avoidant coping style, the general tendency to deal with stressful situations by turning one's attention away from stress-related cues (Krohne, 1996; Krohne et al., 2000), has been found associated with hypertension (e.g., Rutledge & Linden, 2003) and with elevated cardiovascular reactivity to stress (Kohlmann, Weidner, & Messina, 1996; Schwerdtfeger & Rathner, in press; Schwerdtfeger, Schmukle, & Egloff, 2005; Weinberger et al., 1979). A meta-analysis on coping strategies in stressful situations indicates, however, that avoidance might be a functional strategy in reducing stress reactions in the short run (Suls & Fletcher, 1985). Translating this to cognitively demanding situations, avoidant coping could be useful when assuming that cardiac arousal may distract the operator during task performance.

An additional aspect of personality that has been found to influence cardiovascular changes in response to mental workload is dispositional self-focused attention (Silvia, Jones, Kelly, & Zibaie, 2011), which is further an important moderator for cognitive, motivational, and emotional processes (e.g., Buss & Scheier, 1976; Fenigstein, 2009; Scheier & Carver, 1983). Self-focused individuals are assumed to be more sensitive to task demands and to be more engaged in task performance as well as self-evaluation. Also perceived or anticipated discrepancies between actual and desired performance may be reflected in physiological measures since cardiovascular reactivity has mainly been reported for highly demanding tasks (Silvia et al., 2011; Silvia, Kelly, Zibaie, Nardello, & Moore, 2013).

For a comprehensive assessment of operator load, physiological measures are often combined with well-established self-report measures of mental workload. Intriguingly, the relationship between autonomic and self-reported arousal has shown ample consistency over time, a characteristic that is immanent to traits (Schwerdtfeger et al., 2006), and is accordingly suited to predict future performance of operators. In order to evaluate the combination of physiological and self-report measures of mental workload, we also aimed at investigating whether the relationship between both types of measures is impacted by personality traits. This research question could have particular implications for the selection and training of pilots, given that an accurate self-assessment of mental capacity and performance is one of the core requirements. Empirical findings on mental workload and stress indicate that personality traits, especially negative affectivity and cognitive avoidant coping, moderate the relationship between autonomic reactivity to mental workload and self-reports thereof (Newton & Contrada, 1992; Tomaka & Blascovich, 1994). Dissociations between autonomic and self-reported arousal were stronger in individuals scoring high on negative affectivity (participants indicated higher arousal levels than physiologically measured) and cognitive avoidant coping (participants indicated lower arousal levels than physiologically measured).

In sum, the objectives of our study were to investigate whether personality traits account for individual differences in cardiorespiratory measures during resting states and mental workload and to determine the influence of personality traits on the relationship between cardiorespiratory and self-report measures of mental workload. To this end, we assessed basic and variability measures of heart rate and respiratory rate as well as $pCO_2$ in a sample of applicants for pilot training, both during rest periods and multiple task performance. We obtained neuroticism, trait anxiety, and worry in order to cover emotional as well as cognitive aspects of negative affectivity traits. In addition, we included dispositional avoidant coping and self-focused attention as trait variables. Self-reports of experienced task load and emotional states were taken after resting and task periods to capture individual appraisals. We hypothesized a stronger cardiorespiratory responding to mental workload in individuals that are characterized by negative affectivity. Cognitive avoidant coping was expected to be a functional strategy for temporary cognitive load and to reduce cardiorespiratory reactivity, whereas trait attentional self-focus was hypothesized to increase the cardiorespiratory response. Finally, negative affectivity and cognitive avoidant coping were expected to moderate the link between cardiorespiratory and self-report measures of mental workload.

## 6.3 Methods

*Participants*

The total sample consisted of 118 male pilot applicants who underwent psychological aptitude testing at the German Aerospace Center (Hamburg, Germany) and volunteered for this study subsequent to their regular assessment. Only healthy candidates who were non-smokers and had refrained from stimulants such as caffeine prior to the experiment were included. The data of three participants were excluded because of movement artifacts. The remaining 115 participants were between 18 and 43 years old, with a mean of 21.5 years (*SD* = 3.9). Due to equipment constraints, respiratory data were obtained and analyzed on a subsample of 61 participants (*M* = 21.8 years, *SD* = 4.2). For the analysis of heart rate variability (HRV), three additional participants had to be excluded due to invalid data sets. Before the experiment, all candidates gave their informed consent. They received 25 euros for their participation. The experiment was approved by the ethics committee of the Faculty of Psychology and Educational Sciences, University of Leuven.

*Personality questionnaires*

Three constructs of negative affectivity were assessed: neuroticism, trait anxiety, and worry. To measure neuroticism, we used the NEO Five-Factor Inventory (NEO-FFI; German version: Borkenau & Ostendorf, 2008). The neuroticism scale comprises 12 statements about general behaviors and stress responses that were to be answered on a five-point scale ranging from “Strongly disagree” to “Strongly agree”. Internal consistency was acceptable with Cronbach’s $\alpha$ = .73 in the present study. The trait anxiety scale of the State-Trait-Anxiety Inventory (STAI; German version: Laux, Glanzmann, Schaffner, & Spielberger, 1981) was administered to measure trait anxiety. This scale consists of 20 statements about the general condition and mental state of the participant. These items are answered on a four-point scale from "Almost never" to "Almost always" (Cronbach's $\alpha$ = .88). Worry was assessed using the Penn State Worry Questionnaire (PSWQ; German version: Stöber, 1995) which includes 16 items covering the occurrence of and dealing with worries. Response options ranged from "Not at all typical of me" to "Very typical of me" and were indicated on a five-point scale (Cronbach's $\alpha$ = .86).

To measure cognitive avoidant coping style we administered the original German version of the Mainz Coping Inventory (Angstbewältigungs-Inventar – ABI; Krohne & Egloff, 1999). Four fictitious ego-threatening scenarios of the stimulus-response inventory were presented together with ten possible coping strategies that were either vigilant or avoidant. Participants had to indicate for each response whether the hypothetical way of coping applied to them or not (Cronbach's $\alpha$ = .71).

Dispositional attentional focus on the self was assessed using a German questionnaire on self-focus traits (Fragebogen zur Erfassung dispositionaler Selbstaufmerksamkeit – SAM; Filipp & Freudenberg, 1989). The scale on private self-focus measures the tendency to focus one's attention on private or internal states such as feelings and bodily sensations whereas the scale on public self-focus measures the tendency to focus on external aspects of the self. The questionnaire contains 27 statements that were answered on a five-point scale from "Strongly disagree" to "Strongly agree". Internal consistency was acceptable with Cronbach's $\alpha$ = .72 for private self-focus but questionable with Cronbach's $\alpha$ = .61 for public self-focus in this study. As a consequence, only the scale on private self-focus was used to assess self-oriented attentional focus.

*Task load and affective evaluations*

Self-report measures of task load and affect were obtained after the resting baseline, task, and recovery period using the NASA Task Load Index (NASA-TLX; Hart & Staveland, 1988) and scales on valence and arousal of the Self-Assessment Manikin (SAM; Bradley & Lang, 1994), respectively. The NASA-TLX is a well-validated and widely used measure in human factors and ergonomics, comprising six scales on different aspects of operator load (mental demands, physical demands, temporal demands, performance, effort, and frustration) which are rated on scale ranging from 0 to 20. The SAM is a non-verbal measurement technique that uses graphic manikins to indicate the different steps of affective evaluation scales. In the present study, we used nine-point scales in order to differentiate as much as possible between intra- and interindividual feelings and arousal. The valence-scale describes positive or negative feelings ranging from "unhappy/down" (= 1) to "happy/satisfied" (= 9), while the arousal-scale describes the experienced vigilance ranging from "bored/relaxed" (= 1) to "excited" (= 9).

*Physiological measures*

Cardiac activity was monitored with three Ag/AgCl Kendall electrodes that were attached to the chest in a bipolar configuration. The electrocardiogram (ECG) was sampled at 1000 Hz and exported at 400 Hz. The HealthLab software (SpaceBit GmbH, Eberswalde, Germany) was used to export the raw ECG in separate data records for each individual and period. For the computation of heart rate (HR) and HRV, absolute interbeat intervals (IBI) were processed by means of ARTiiFACT (Kaufmann, Sütterlin, Schulz, & Vögele, 2011). This software was also used for the detection of artifacts and respective corrections by linear interpolation after visual inspection of the artifacts. The data records of three participants had to be excluded because of excessive artifacts (> 20). Time-domain measures of HRV included the root-mean-square of successive differences in NN intervals (rMSSD) and the number of successive NN interval differences being greater than 50 ms divided by the total number of NN intervals (pNN50). For frequency-domain measures, power values were computed for the high-frequency (HF) band ranging from .15 to .40 Hz and for the low-frequency (LF) band ranging from .04 to .15 Hz and expressed in power ($ms^2$). Spectral decomposition was performed using the fast Fourier transformation. Prior to the statistical analysis, HRV measures were $\log_{10}$-transformed to obtain normal distributions.

A mainstream capnograph (Nihon Kohden Europe GmbH, Rosbach, v.d.H., Germany) was used to record respiratory rate (RR) and $pCO_2$ with an infrared sensor that was attached by a nose clip. Therefore, participants were asked to remain silent and to breathe only through their nose during data acquisition. The continuous respiratory signal was sampled at a frequency of 20 Hz. Again, a separate data record was created for each individual and experimental period. End-tidal plateau values for $pCO_2$ ($petCO_2$) were extracted by means of ANSLAB (Wilhelm & Peyk, 2005) and expressed in mmHg. Linear interpolation was used to correct detected outliers (± 2*SD*; within one data record) after visual inspection.

In the present study, we used the coefficient of variation (CV) and autocorrelation (AR) to determine the variability in RR. While the CV is regarded as a measure of total variability, the AR is regarded as a measure of structured variability which here was computed by correlating each breath of a breath string with the following one in this breath string (Tobin et al., 1995).

The HealthLab hardware (Koralewski Industrie-Elektronik oHG, Hambühren, Germany) and software (SpaceBit GmbH, Eberswalde, Germany) were used to synchronize readings from the ECG and capnography channels.

### *Procedure*

To control for circadian variation in cognitive performance and physiological parameters, all experiments were run around 5 pm when candidates had completed their regular assessment. After the attachment of physiological recording devices, participants completed a set of questionnaires. They were instructed not to move and speak during the experimental periods because of artifacts that might be caused in the cardiac and respiratory data. In addition, an accelerometer was attached to the thorax and the experimenter controlled visually for substantial body movements. When physiological signals had stabilized, participants were asked to start the computer-based experiment according to the instructions presented on the screen. In order to manipulate mental workload, the experiment was composed of a resting baseline (BL), a vanilla baseline (V-BL), a multiple task (MT), and a recovery (RC) period, each lasting for 6 minutes. In order to obtain stationary data for the computation of variability measures and to exclude single artifacts that occurred at the beginning and end of a few periods, we only analyzed the data of five-minute time windows by deleting the first and last 30 seconds of each six-minute record. During the resting baseline, a fixation cross was presented on the computer screen which had to be focused throughout the period. The vanilla baseline was included to limit possible anticipatory arousal by performing a computer-based low intensity signal detection task, which required participants to monitor four dots and count the occasions of one dot flashing red (Jennings et al., 1992). In the present experiment, however, the vigilance task was not accompanied by a reduced cardiorespiratory response. We therefore decided to use only resting baseline scores for the determination of cardiorespiratory reactivity (baseline-to-task changes). The multiple task comprised three single tasks measuring perceptual speed, spatial orientation, and working memory which had to be performed simultaneously. For a detailed description of the multiple task see Grassmann et al. (in press). During the recovery period, participants watched an aquatic movie that was presented with relaxing background music (Piferi, Kline, Younger, & Lawler, 2000).

### *Statistical analysis*

Cardiorespiratory changes between periods were analyzed by two repeated-measures multivariate analyses of variance (MANOVAs) using Pillai’s trace on cardiac and respiratory measures with period (baseline/multiple task/recovery) as a within-subject variable. Changes in self-reported mental workload were investigated across periods by three separate repeated-measures ANOVAs on task load, valence, and arousal ratings with period (baseline/multiple task/recovery) as a within-subject variable. Degrees of freedom were adjusted by Greenhouse-Geisser corrections if the assumption of sphericity was violated. Bonferroni-corrected t-tests were used for the post-hoc comparisons of experimental periods. Since age was not significant as a covariate in the initial analyses (multivariate analyses of covariance), we did not control for age in the repeated-measures analyses of cardiorespiratory parameters.

Because of the theoretical relation between the selected trait variables we computed Spearman’s correlation coefficients for the non-normally distributed trait variables neuroticism, trait anxiety, worry, and cognitive avoidant coping and the normally distributed self-focused attention scale. These analyses revealed high intercorrelations between neuroticism, trait anxiety, worry, and cognitive avoidant coping (Table 4) suggesting the usefulness of reducing these data to underlying factors. The items of the neuroticism, trait anxiety, worry, and cognitive avoidant coping measures were hence subjected to a principal component analysis. A scree plot test suggested to retain two components that were also in line with theoretical considerations. Due to their indicator characteristics, we labelled factor 1 *negative affectivity* (NA) and factor 2 *cognitive avoidant coping* (CAV). Because theory and research suggest that NA and CAV are correlated (Endler & Parker, 1990; Gomez, Holmberg, Bounds, Fullarton, & Gomez, 1999; Krohne et al., 2000), an oblimin rotation was chosen for the final model. A total of eight items were deleted because they did not have a primary factor loading or cross-loading of .3 or above. The two-factor solution explained 59% of the variance. The extracted factors NA and CAV were saved as variables using the Anderson-Rubin method (DiStefano, Zhu, & Mindrila, 2009). Internal consistency was satisfactory with Cronbach's $\alpha$ = .90 for NA and Cronbach's $\alpha$ =.64 for CAV.

Table 4. Pearson's correlations between trait variables (*N* = 115).

| | Neuroticism | Trait anxiety | Worry | Cognitive avoidant coping |
|---|---|---|---|---|
| Trait anxiety | .70*** | | | |
| Worry | .54*** | .67*** | | |
| Cognitive avoidant coping | -.30** | -.37*** | -.24** | |
| Self-focused attention | .02 | .04 | .02 | .05 |

*Note*. * *p* < .05, ** *p* < .01, *** *p* < .001.

To investigate the relationship between the trait variables NA, CAV, self-focused attention, and cardiorespiratory measures, we first analyzed the associations between trait variables and cardiorespiratory measures obtained during baseline and recovery using bivariate Pearson's correlation analyses. Second, we performed separate hierarchical regression analyses of the cardiorespiratory measures during task performance on personality traits while controlling for initial values. Besides age, the according cardiorespiratory baseline score was entered as a covariate in the first step, the trait variables NA, CAV, and self-focused attention were entered in the second step. The final regression models were run after excluding non-significant covariates and predictors.

In order to test whether personality traits moderated the relationship between physiological and self-report measures of mental workload, hierarchical regression analyses of basic cardiorespiratory measures (HR, RR, $petCO_2$) on self-reports and trait variables were conducted. We performed these analyses for both resting and task load conditions. In the first step, age was entered as a covariate. Personality traits as well as self-reported task load, valence, and arousal were entered in the second step and interaction terms of trait variables and self-reports in the third step. To build the final regression model, we re-ran analyses excluding non-significant covariates, predictors, and interaction terms. All analyses were conducted using SPSS 21.0 for Windows (SPSS Inc., Chicago, IL).

## 6.4 Results

Intercorrelations and descriptives of the obtained trait variables are presented in Tables 4 and 5, respectively. Because of the high intercorrelations between neuroticism, trait anxiety, worry, and cognitive avoidant coping we used the extracted factors NA and CAV for statistical analysis. The obtained factor scores for NA and CAV are standard scores ($M = 0$, $SD = 1$).

Table 5. Means (*M*) and standard deviations (*SD*) for trait variables in the total sample (*N* = 115) and the subsample with respiratory data sets (*n* = 61).

| | *N* = 115 | | *n* = 61 | |
|---|---|---|---|---|
| | *M* | *SD* | *M* | *SD* |
| Neuroticism (1–5) | 2.10 | .53 | 2.10 | .51 |
| Trait anxiety (20–80) | 33.59 | 7.90 | 33.50 | 7.59 |
| Worry (16–80) | 39.30 | 9.98 | 39.61 | 9.43 |
| Cognitive avoidant coping (0–20) | 11.72 | 2.80 | 11.59 | 3.51 |
| Self-focused attention (13–65) | 45.24 | 5.24 | 45.54 | 5.19 |

*Note*. Numbers in parentheses indicate the range of possible mean scores.

*Cardiorespiratory and self-reported responses to mental workload*

The rmMANOVA revealed a significant effect of period on HR, rMSSD, pNN50, HF, and LF ($V = 0.74$, $F(10, 110) = 28.30$, $p < .001$). Statistical parameters of the univariate analyses are displayed in Table 6. HR increased from baseline to task and decreased during the subsequent recovery period. All HRV measures (rMSSD, pNN50, HF, LF) were reduced during task performance and showed full effects of recovery after the task. Also for respiration, the rmMANOVA revealed a significant effect of period; multivariate and univariate statistics of the respiratory data have been reported in Grassmann et al. (in press).

The rmANOVA performed on experienced task load as measured by the NASA-TLX showed an increase from baseline to task ($p < .001$) and a decrease from task to recovery ($p < .001$; $F(1.81, 206.82) = 635.09$, $p < .001$, $\eta_p^2 = .85$). When analyzing the self-reported affective states that were obtained with the SAM, the rmANOVA revealed a significant effect for period in both self-reported valence ($F(1.87, 213.46) = 43.63$, $p < .001$, $\eta_p^2 = .28$) and arousal ($F(1.88, 214.35) = 199.99$, $p < .001$, $\eta_p^2 = .64$). Compared to baseline, participants reported a less positive state ($p < .05$) and a higher arousal ($p < .001$) during the task performance. After completion of the task, valence ratings increased ($p < .001$) and arousal ratings decreased ($p < .001$).

Table 6. Means (*M*), standard deviations (*SD*), and repeated-measures ANOVA results (including effect size $\eta_p^2$) for cardiorespiratory study variables.

| | | BL | | MT | | RC | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | *N* | *M* | *SD* | *M* | *SD* | *M* | *SD* | df | $df_{error}$ | *F* | *p* | $\eta_p^2$ |
| HR | 115 | 71.32[a] | 11.12 | 77.37[b] | 12.02 | 70.58[c] | 10.89 | 1.58 | 180.48 | 172.69 | <.001 | .60 |
| rMSSD | 112 | 46.15[a] | 25.65 | 37.74[b] | 23.87 | 45.16[a] | 23.89 | 1.51 | 167.80 | 29.76 | <.001 | .21 |
| pNN50 | 112 | 23.56[a] | 20.76 | 16.51[b] | 18.06 | 22.73[a] | 20.18 | 1.54 | 171.37 | 29.63 | <.001 | .21 |
| HF | 112 | 1009.33[a] | 1052.45 | 687.43[b] | 1221.17 | 938.26[a] | 1118.61 | 1.70 | 188.73 | 25.60 | <.001 | .19 |
| LF | 112 | 2275.38[a] | 3236.53 | 1289.84[b] | 1239.32 | 1796.70[a] | 1585.80 | 1.80 | 199.55 | 10.60 | <.001 | .09 |

*Note*. HR: heart rate (beats/min), rMSSD: root mean square of successive differences in inter-beat intervals (ms), pNN50: proportion of successive inter-beat intervals difference > 50 ms (%), HF: high-frequency power (ms$^2$), LF: low-frequency power (ms$^2$), BL: baseline, MT: multiple task, RC: recovery.

[a, b, c] Different letters in the same row indicate significant differences between periods ($p < .05$).

*Individual differences in cardiorespiratory response measures*

The correlation analyses on trait variables and cardiorespiratory measures during baseline and recovery revealed that self-focused attention was associated with lower total variability in RR during baseline ($r = -.28$, $n = 61$, $p < .01$) and recovery ($r = -.28$, $n = 61$, $p < .05$) and further with lower RR ($r = -.28$, $n = 61$, $p < .01$) and higher petCO2 levels during recovery ($r = .29$, $n = 61$, $p < .05$). HR and HRV during resting conditions were not related to self-focused attention. No significant correlations were found for NA or CAV and the cardiorespiratory measures obtained during baseline and recovery.

Regression analyses of cardiorespiratory reactivity measures on trait variables showed that reactivity in HR was negatively related to CAV and that reactivity in RR was negatively related to self-focused attention. Changes in $petCO_2$ and cardiorespiratory variability measures were not affected by any of the trait variables. The final regression models for HR and RR are displayed in Tables 7 and 8, respectively.

Table 7. Hierarchical regression of heart rate during multiple task performance ($N = 115$).

| | *b* | *SE* (b) | *p* | $\Delta R^2$ |
|---|---|---|---|---|
| 1. HR (BL) | .99 | .04 | <.001 | .83** |
| 2. CAV | -1.10 | .46 | .019 | .01* |
| Constant | 8.54 | 3.01 | .005 | |
| | $F(2, 112) = 295.04$, $p < .001$, $R^2 = .84$, $R^2_{adj.} = .84$ | | | |

*Note*. HR: heart rate, CAV: cognitive avoidant coping (factor), BL: baseline, *b*: unstandardized regression coefficient, *SE*: standard error.
* $p < .05$, ** $p < .001$.

Table 8. Hierarchical regression of respiratory rate during multiple task performance (*n* = 61).

| | *b* | *SE* (b) | *p* | ΔR² |
|---|---|---|---|---|
| 1. RR (BL) | .36 | .09 | <.001 | .20** |
| 2. Self-focused attention | -.22 | .07 | .001 | .14* |
| Constant | 14.58 | 1.18 | <.001 | |
| | $F(2, 58) = 14.82$, $p < .001$, $R^2 = .34$, $R^2_{adj.} = .32$ | | | |

*Note*. RR: respiratory rate, BL: baseline, *b*: unstandardized regression coefficient, *SE*: standard error.
* $p < .01$, ** $p < .001$.

*Individual differences in the relationship between cardiorespiratory and self-reported response measures*

Hierarchical regression analyses of basic cardiorespiratory measures on self-report of mental workload revealed that NA interacted with self-reported arousal when predicting HR during baseline and multiple task performance. Self-focused attention and CAV did not affect the relationship between cardiac and self-reported arousal. No significant effects were found when regressing RR and petCO2 on self-report measures of mental workload. Table 9 shows the significant findings for HR. After controlling for age, the experience of arousal significantly contributed to the variance of HR (p <.01) during baseline as well as multiple task performance. In addition, self-reported arousal interacted with NA to predict HR (p < .05). However, when entering baseline HR as a covariate to control for initial values, the relationship between HR and experienced arousal was no longer moderated by NA. This suggests that the obtained interaction effect did not lead to an incremental explanation of variance in HR under mental workload than under resting conditions. To illustrate the interaction between self-reported arousal and NA, we divided the sample using a median split into pilot candidates scoring high and low on NA. In the high-NA group, Pearson's correlation coefficients revealed a significant association between HR and self-reported arousal for both baseline (*r* = .49, *p* < .001) and multiple task periods (*r* = .44, *p* < .001). There was no significant association in the group scoring low on NA.

Table 9. Hierarchical regression of heart rate during baseline and multiple task performance (*N* = 115).

| | BL | | | | MT | | | |
|---|---|---|---|---|---|---|---|---|
| | *b* | *SE* (b) | *p* | ΔR² | *b* | *SE* (b) | *p* | ΔR² |
| 1. Age | .55 | .26 | .040 | .04* | .60 | .29 | .038 | .04* |
| 2. Self-reported arousal | 2.23 | .77 | .005 | | 1.78 | .65 | .007 | |
| NA | -6.74 | 7.48 | .370 | .07* | -1.00 | 8.02 | .901 | .06* |
| 3. Self-reported arousal x NA | 13.98 | 6.18 | .026 | .04* | 8.30 | 4.60 | .047 | .03* |
| Constant | 58.15 | 6.72 | <.001 | | 64.35 | 7.24 | <.001 | |
| | $F(4, 110) = 4.68, p = .002, R^2 = .15, R^2_{adj.} = .11$ | | | | $F(4, 110) = 3.91, p = .005, R^2 = .12, R^2_{adj.} = .09$ | | | |

*Note.* NA: negative affectivity, BL: baseline, MT: multiple task, *b*: unstandardized regression coefficient, *SE*: standard error.
* *p* < .05.

## 6.5 Discussion

The main objective of this study was to examine whether physiological assessments of operator load are impacted by individual trait characteristics. For this purpose, we explored trait-related differences in cardiorespiratory measures during baseline, task, and recovery periods. In addition, we investigated the role of personality traits in the relationship between cardiorespiratory and self-report measures of mental workload since physiological parameters are typically completed with self-report measures to achieve an integral assessment of operator load. Of note, by testing a sample of pilot applicants, we focused on a highly motivated and homogeneous sample. A comprehensive evaluation of physiological and subjective markers of mental workload in this group might have particular relevance for human well-being and safety in aviation operators.

Cardiorespiratory and self-report measures of mental workload demonstrated that the applied multiple task induced substantial levels of operator load which is indicated by medium to strong effect sizes. In line with prevailing findings in the literature, heart rate increased from baseline to task whereas HRV was reduced while performing the task (e.g., Boucsein et al., 2011; Brookings et al., 1996; Hansen et al., 2003). The cardiac measures fully recovered during the subsequent relaxation period. Overall findings for respiration have been discussed earlier (Grassmann et al., in press). In accordance with previous findings (Brookings et al., 1996; Fournier et al., 1999; Vlemincx et al., 2012; Wientjes et al., 1998), respiratory rate increased whereas variability measures and $petCO_2$ were reduced in response to mental workload. Also task load ratings and self-reported arousal reflected our experimental periods by distinctly increasing from baseline to task and decreasing during recovery. Valence ratings were only slightly decreased in response to the task and were highest during the recovery period.

The present analyses of interindividual variation in cardiorespiratory measures revealed that, during rest, high self-focused attention was related to lower respiratory rate, higher $petCO_2$ levels, and reduced total variability in respiratory rate. While similar findings have been reported for negative affectivity (Dhokalia et al., 1998; Van Diest et al., 2003; Van Diest et al., 2006), there are, to our knowledge, no prior studies investigating trait self-focused attention and respiratory behavior at rest. Since correlations were of moderate magnitude and not consistently found for baseline *and* recovery it requires further investigation whether high self-focused attention is typically accompanied by reduced basic and variability measures of respiratory rate and by increased $petCO_2$ levels. Importantly, our results show that self-focused attention accounted for 14% of the variance in respiratory reactivity to mental workload (Table 8). Also when analyzing baseline-to-task changes, a higher attentional self-focus was associated with lower respiratory rate, even when controlling for initial values of respiratory rate. This finding suggests that, against our expectations, self-focused attention inhibits regular respiratory behavior, a non-pathological phenomenon which is also referred to as strained breathing.

According to Fokkema (1999), strained breathing is characterized by prolonged expiration, often resulting in elevated $CO_2$ levels, and typically occurs in response to mental stress and threatening situations. Fokkema (1999) points out that strained breathing may be functional by counteracting hyperventilation and increasing cerebral circulation, hence benefiting cognitive function. However, this explanation is inconsistent with data we recently reported on respiratory reactivity to mental workload, showing that an increase rather than a reduction in respiratory rate – if not exceeding metabolic demands – correlates with higher cognitive performance (Grassmann et al., in press). Whether a strained respiratory pattern is rather useful or disadvantageous for reaching one's performance optimum is, however, beyond the scope of this paper and remains to be investigated further.

In line with our hypothesis, we found that cardiac reactivity to mental workload was lower in individuals reporting a tendency to avoid potentially threatening stimuli by diverting their attention. Even though avoidant coping explained only 1% of variance in heart rate changes from baseline to task (Table 7), we consider this finding noteworthy because it contrasts with a number of previous studies in health psychology. These studies showed that cognitive avoidance was generally related to higher cardiac reactivity and might pose a risk factor for hypertension (Schwerdtfeger & Rathner, in press; Schwerdtfeger et al., 2005; Weinberger et al. 1979). The present result, however, suggests that avoidant coping might be useful when dealing with a transient mentally demanding task. This interpretation is supported by additional explorative correlation analyses on CAV and self-reported valence and arousal. These analyses showed that avoidant coping was also associated with positive feelings ($r = .23$, $p < .01$) but not with experienced arousal ($r = -.11$, n.s.) during task performance. The extensive review by Suls and Fletcher (1985) and recent experimental findings (Beasley, Thompson, & Davidson, 2003) on avoidant coping and effects of physical and psychological stressors likewise revealed that avoidant coping strategies might be beneficial for short-term adjustments to external stressors. Favorable effects of cognitive avoidant coping in reducing cardiac reactivity might possibly be used in psychological training concepts for aviation personnel who are regularly confronted with mentally demanding situations.

Against our expectations, negative affectivity was neither associated with cardiorespiratory measures in anticipation of the task or during recovery nor with cardiorespiratory changes from baseline to task. Recent reviews, however, suggest small and medium effects for the relationship between cardiac arousal and single negative affectivity trais (Brosschot et al, 2006; Chida & Hamer, 2008; Myrtek, 1998; Ottaviani et al., 2015). We speculate that our deviating findings are attributable to the specific characteristics of the present sample consisting of young and ambitious male pilot applicants. When monitoring operator load in pilot selection and training, however, our findings suggest that a consideration of cardiorespiratory measures would particularly increase the validity of mental workload assessments when controlling for trait measures of self-focused attention and avoidant coping.

During baseline and task periods, self-reported arousal was positively associated with heart rate but not with HRV. Given that physiological measures are often combined with self-report measures of mental workload, we additionally analyzed whether the obtained association between cardiac and self-report measures is impacted by personality traits. According to our hypothesis, negative affectivity moderated the relationship between heart rate and self-reported arousal. After controlling for age and including self-reported arousal as a significant predictor, the state-trait interaction additionally explained 4% of variance in heart rate during baseline and 3% during the performance of the multiple task. When comparing individuals scoring high and low on negative affectivity, elevated cardiac arousal was associated with higher levels of experienced arousal only in the group with high negative affectivity scores. We speculate that this group was more sensitive to cardiac changes, which may have increased the experienced arousal level. In line with this assumption, previous studies indeed reported that negative affectivity is accompanied by over-reporting arousal levels when relating self-reports with autonomic measures (Newton & Contrada, 1992; Tomaka & Blascovich, 1994). The present observation that the covariation of cardiac and self-report measures of mental workload is partly moderated by trait characteristics suggests that an inclusion of personality traits may also be useful when validating physiological measurement techniques or evaluating the accuracy of self-ratings of mental workload in pilot selection. Interestingly, our analyses revealed that self-reported arousal during baseline and task was only related to heart rate but not to respiratory rate. This could imply that respiratory measures reveal incremental information about operator load and would be a useful supplement for the assessment of mental workload.

In summary, we found evidence that individual differences in cardiorespiratory measures of operator load are related to individual trait characteristics, even though prospective studies are needed to replicate the present findings for different types of mental workload using study samples which include female operators and are less restricted in terms of education, training, and motivation as well as psychological and physical condition. Whereas reactivity in heart rate was only slightly affected by cognitive avoidant coping, respiratory measures were clearly influenced by dispositional self-focused attention, suggesting that an attentional self-focus attenuates respiratory reactivity to mental workload. In addition, the obtained association between cardiac and self-report measures of arousal was contingent on negative affectivity. We conclude that an incorporation of operator trait characteristics might reduce unexplained variance and contribute to a more integrative framework when investigating and applying psychophysiological methods for the assessment of mental workload.

# 7 General discussion

The present findings and conclusions will be discussed first regarding the general usefulness of cardiorespiratory parameters for the assessment of mental load, and second from an evaluation perspective on the assessment of stress resistance in pilot selection.

## 7.1 Cardiorespiratory parameters in the measurement of mental load

The present review study was conducted to give an overview on the available research on respiration under mental load. Among the basic ventilatory measures, respiratory rate appears to be the most useful measure as it can be obtained easy and unobtrusively and clearly reflects metabolic changes in response to mental load. Apart from an elevated metabolic need, increases in ventilation are assumed to result from psychological processes such as learning (Stegen et al., 1999; Zaman et al., 2014). Moreover, reported indications for a reduced correlated variability in respiratory rate and a less efficient gas exchange in several studies are in line with the experimental findings of our own study (Chapter 5), but require further validation due to the small database of our review. Also the variety of different task types, which had to be combined for the present review, as well as the inconsistent findings on habituation effects of respiratory responses call for additional research.

A major conclusion from our review is that future research on respiratory behavior under mental load is crucial and should follow a structured and integrated approach as outlined in our recommendations (Chapter 4). Main objectives for prospective studies are the investigation of less established measures such as respiratory variability, their integration with validated physiological measures, the consideration of individual differences, and the systematic assessment of respiratory effects of different types of cognitive processes. As argued previously (Gaillard & Wientjes, 1994; Jerusalem & Schwarzer, 1992) and supported by our review findings, a concurrent performance feedback may cause stress in addition to the mental load imposed. Therefore, a strict distinction between cognitive demands and emotional demands in the experimental design seems essential for an accurate investigation of mental load.

The main purpose of our experimental study was to analyze cardiorespiratory parameters in a mentally demanding situation without emotional manipulation or potentially threatening cues such as evaluative feedback during performance. As outlined before, the role of respiration has often been neglected in mental load assessments – despite the fact that respiration may influence cardiac regulation at different levels (e.g., through vagal stimulation; Angelone & Coulter, 1964; Rosenblum et al., 2002). Whereas related phenomena such as respiratory sinus arrhythmia have attracted the interest of researchers during the recent years (e.g., Song & Lehrer, 2003; Yasuma & Hayano, 2004), the use of respiratory measures as primary indicators of mental load has still been disregarded. For this reason, our first analyses (Chapter 5) focused on respiration, while cardiac measures were included in our analyses on individual differences (Chapter 6) in order to link our research to the broad empirical database that is available in the workload literature.

In the present experimental study, we aimed at evaluating the sensitivity of respiratory measures to mental load, associations between respiratory and performance measures as well as the role of individual differences in cardiorespiratory reactivity.[13] Our findings support the usefulness of respiratory rate as well as total and correlated variability in respiratory rate for the measurement of operator load. While the strong increase in respiratory rate and the decrease in correlated variability correspond with existing evidence (Mehler et al., 2009; Pattyn et al., 2010; Veltman & Gaillard, 1998; Vlemincx et al., 2011; Wientjes et al., 1998), the decrease in total variability in respiratory rate differs from data reported by Vlemincx et al. (2011) and Novak et al. (2012), who found no significant alterations from baseline to a mental arithmetic task. It might be speculated that differences are due to diverse cognitive demands which were probably higher in the present multiple task. Future research comparing different types and levels of task demands would be useful to clarify this issue.

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[13] Our results on the sensitivity of cardiac measures to mental load are discussed below (see p. 80).

Also $petCO_2$ was sensitive to task load but, in contrast to respiratory rate and variability measures, not fully restored during the recovery period. This implies that $petCO_2$ would not be suited to monitor short-term changes in mental load, but to detect individuals with a tendency to ventilate in excess of metabolic need when operating in highly demanding situations. Interestingly, effects of prolonged overbreathing have also been found in field studies (Harding, 1987; Wientjes et al., 1996). A particular interest of our study was to investigate whether decreases in $petCO_2$ would also lead to performance decrements. Overall, the moderate decrease in $petCO_2$ was not related to performance measures, which is also in line with previous studies reporting performance decrements mainly for individuals showing hypocapnic levels of overbreathing (Karavidas et al., 2010; Matthews et al., 2010; McCarthy et al., 1995; Van Diest et al., 2000). However, given that only three individuals of the present sample ($n = 61$) showed hypocapnic hyperventilation under a multiple task lasting for merely six minutes, we assume that hypocapnic overbreathing may occur more frequently in higher demanding and prolonged situations. We thus consider $petCO_2$ to be a relevant measure when ensuring operator performance is of utmost importance under extreme workload conditions such as human space flight.

An interesting research question that remains for prospective studies is whether respiration, particularly $petCO_2$, might be suited to distinguish between mental load and stress. Large individual differences in respiratory reactivity such as overbreathing (hyperventilation) *and* breathing inhibition (hypoventilation) imply that inappropriate respiratory changes might particularly occur in operators who are vulnerable to stress (Anderson & Chesney, 2002; Van Diest et al., 2003). Also in the present study on individual differences (Chapter 6) we found that individuals characterized by high self-focused attention showed a specific respiratory pattern under mental load (reduced respiratory rate and increased $petCO_2$). Reported after-effects additionally suggest that $petCO_2$ might be a valuable measure to assess whether the operator experienced the test situation rather as a challenge or a threat. According to the different energetic processes which are assigned to the concepts of mental load and stress (Chapter 2), we would expect that a prolonged $petCO_2$ recovery is related to negative emotions and stress. While cardiac arousal has been found to increase in both challenging and threatening situations (Seery, 2013), we speculate that $petCO_2$ is a promising measure to detect stress-related respiratory changes (e.g., hypocapnic overbreathing, prolonged $petCO_2$ recovery) in individuals who experience a negative state in mentally demanding situations.

Since cognitive performance constitutes a valid measure of operator load, we also investigated the relationship between respiratory rate and variability measures on the one hand and performance measures on the other hand. A better performance in the multiple task was associated with a lower respiratory rate during baseline, a stronger increase from baseline to task, and a stronger decrease from task to recovery. This suggests that a flexible respiratory system, allowing quick mobilization of energetic resources and quick return to rest, is associated with a better task performance which is in line with existing findings on the beneficial effects of cardiac variability (e.g., Segerstrom & Nes, 2007; Thayer et al., 2009). Also small but significant positive correlations between correlated variability in respiratory rate at rest and task performance support the reasoning that respiratory flexibility is beneficial for cognitive processing. In addition, a comparison of pilot candidates who passed the aptitude testing and those who failed showed that a better performance in the cognitive aptitude exam was related to a lower respiratory rate during resting conditions and a stronger increase in response to mental load. While traditional research on mental load assessments has focused on the mere amount of physiological reactivity (mainly baseline-to-task changes), our results on respiration suggest that analyzing the entire response pattern over resting and task conditions would reveal additional information.

A further aim of our experiment was to refine mental load assessments by taking individual differences into account. To this end, we analyzed possible covariation between cardiac and respiratory parameters on the one hand and personality traits on the other hand. Overall, heart rate and HRV were clearly sensitive to mental load which corresponds with previous findings (Backs & Seljos, 1994; Boucsein et al., 2011; Hansen et al., 2003; Mulder & Mulder, 1981; Veltman & Gaillard, 1998). Considering the large effect size for heart rate and medium effect sizes for measures reflecting HRV as well as the convenience of ECG recordings, we suggest that cardiac measures are well-suited as indicators of mental load. While cardiorespiratory responses were not systematically associated with negative affectivity traits, we found that self-focused attention was related to changes in respiratory rate from baseline to task. Reactivity in heart rate was marginally affected by cognitive avoidant coping. Nevertheless, person-related differences in respiratory reactivity indicate that an incorporation of individual differences would reduce unexplained variance and slightly improve the assessment of operator load. However, the limited findings on trait-related differences in cardiorespiratory activation highlight the importance of studying the interaction between personality traits and situational characteristics. The recent assumption that individual appraisals of a situation trigger context-related traits that subsequently lead to a certain state and behavioral response (Stemmler & Wacker, 2010) should be evaluated by a systematic investigation of different mentally demanding situations. Of note, the need for an integrative approach is also supported by the strong interindividual variation that we found in petCO$_2$ and the hypocapnic breathing we observed in three participants. This might be indicative for individually different appraisals of the situation.

Taken together, the findings of our studies indicate that cardiorespiratory measures are sensitive to mental load and would be a promising supplement to performance measures and rating scales of mental load. Besides heart rate, the analysis of respiratory rate appears to be especially suited for application and field studies because of the inexpensive and convenient measurement techniques that are available. In addition, we consider gas exchange parameters to be particularly useful as they may reveal additive information over time and volume parameters. Under controlled resting conditions, alterations in O$_2$ consumption and CO$_2$ release may reflect changes in the amount of energy expenditure, while decreases in petCO$_2$ would indicate a mismatch of ventilation and metabolic demand.

## 7.2 Implications for pilot selection

Overall, our experimental findings replicated existing results regarding the sensitivity of cardiorespiratory measures for mental task demands typically occurring in pilot selection and also during flight. Besides the clear effects of mental load on heart rate, also HRV measures significantly differed between task and resting periods. The present studies further show that also respiratory rate clearly indexes changes in mental load. Given that respiratory rate was additionally associated with cognitive performance, we conclude that respiration contains valuable information for diagnostic purposes in pilot selection. As mentioned above, convenient measurement techniques such as a calibrated strain gauge allow a simple and unobtrusive recording of respiratory rate that could easily be applied in several selection tasks. When implementing respiratory measures in the selection procedure, it should generally be considered that computerized manual-response tasks instead of verbal-response tasks would increase not only data quality but also validity. For this reason, specific tasks of the selection procedure such as group discussions should not be used for taking respiratory readings.

Regarding respiratory variability and other timing parameters that appear to be promising, our review showed that the empirical evidence is still sparse. Therefore, future research is needed to validate these measures before applying them in pilot selection. Although pet$CO_2$ decreased significantly during task performance, changes were of moderate magnitude. As a consequence, the usefulness of this measure for diagnostic purposes seems not appropriate in assessment settings that are similar to the present experiment. However, as outlined in the previous section, the strong between-subject variation, hypocapnic hyperventilation in three participants, and a prolonged pet$CO_2$ recovery suggest that pet$CO_2$ may especially be useful in identifying operators with a tendency to hyperventilate. If future research supports the assumption that pet$CO_2$ is a sensitive measure for detecting vulnerability to stress, we suggest including this parameter in high-level assessments such as astronaut and fighter pilot selection. In these areas, samples are typically small and measurement techniques do not have to be as convenient and economical as in routine selection procedures of civil aviation.

Importantly, the fact that a stronger respiratory reactivity was associated with a better performance contradicts heuristics that are used for evaluating stress resistance in mentally demanding situations. As outlined in Chapter 1, diagnostics of stress resistance currently comprise the use of performance measures, self-reports, and observer ratings. Since self-reports might be distorted by social desirability and memory lapse, more importance is attached to the independent ratings of trained observers. For this purpose, frequency and intensity of visible strain symptoms (e.g., dry mouth, stammering, swallowing) are recorded, while candidates perform a set of individual and group tasks. Final evaluations are based on the assumption that candidates showing a high number or intensity of symptoms are more vulnerable to elevated task load. Using such heuristics, however, is controversial as they have not been evaluated and conflict with some of the present findings. Given that a strong respiratory reactivity and quick recovery were associated with a better cognitive performance in pilot candidates, we argue that the analysis of respiratory patterns (i.e., changes from baseline to task) is more appropriate than interpreting observed or measured arousal levels only during task performance. Likewise, also peak levels of other autonomic parameters during task performance might wrongly be interpreted as indicators of vulnerability to stress and should thus be evaluated together with data obtained during resting periods.

The positive relationship between respiratory reactivity and cognitive performance implies that a certain level of autonomic activation is beneficial for cognitive processes, rather indicating an adequate level of energy mobilization. Certainly, this reasoning is not new and could also be referred to traditional theories such as activation-related concepts of mental load, in which the relationship between autonomic arousal and performance is described as a curvilinear or nonlinear function (e.g., Fahrenberg, 1979; Thayer, 1989; Yerkes & Dodson, 1908). Hence, the present findings support the assumed usefulness of a quick and efficient adaption to onset and offset of mental load in aviation (see also Dienstbier, 1989; Kashdan & Rottenberg 2010) for the respiratory system and highlight the need to revise the current rating and evaluation procedures.

Finally, we conclude from our findings on trait-related differences in cardiorespiratory measures of operator load and their association with self-reports, that an incorporation of person-related variables would reduce unexplained variance in predicting job performance. Our findings indicate that negative affectivity traits, attentional focus, and coping behavior may affect the cardiorespiratory response to mental load. In addition, the literature suggests that interoceptive sensitivity and self-esteem, which were not included in the present study, may also be related to appraisal processes and the psychophysiology of mental load (Barrett, Quigley, Bliss-Moreau, & Aronson, 2004; Craig, 2002; Seery, 2011).

An integrative assessment covering performance, self-report, observer-based, and physiological measures should be a primary objective in pilot selection. At present, the available data from task performance, self-reports, and observer ratings are integrated through consensus discussion. Since this procedure, however, is not immune to subjective bias, we suggest developing an integrative model to combine these data in a fully standardized way using explicit decision rules. For example, the different pieces of data being collected for one candidate such as performance measures, self-reports, etc. could be entered into a computer-based system which would generate total scores for each scale of job requirement such as stress resistance and leadership. According to Hoffman's diagnostic model of "paramorphic representations" (1960), we argue that a formal representation of selection, weighting, and combination as, for instance, an algorithm depicting the experience of experts would increase the predictive validity of career prognoses. Research in the field of clinical diagnostics has shown that algorithms which are derived from formal representations are superior to human judgments of experienced psychologists (Dudycha & Naylor, 1966; Goldberg, 1970; Wiggins, 1973).

# References

Aasman, J., Mulder, G., & Mulder, L. J. M. (1987). Operator effort and the measurement of heart rate variability. *Human Factors, 29*, 161–170.

Aickin, M. & Gensler, H. (1996). Adjusting for multiple testing when reporting research results: The Bonferroni vs. Holm methods. *American Journal of Public Health, 86*, 726–728.

Allen, M. T. & Crowell, M. D. (1989). Patterns of autonomic response during laboratory stressors. *Psychophysiology, 26*, 603–614.

Althaus, M., Mulder, L. J. M., Mulder, G., Van Roon, A. M., & Minderaa, R. B. (1998). Influence of respiratory activity on the cardiac response pattern to mental effort. *Psychophysiology, 35*, 420–430.

Anderson, D. E. & Chesney, M. A. (2002). Gender-specific association of perceived stress and inhibited breathing pattern. *International Journal of Behavioral Medicine, 9*, 216–227.

Andreassi, J. L. (1966). Some physiological correlates of verbal learning task difficulty. *Psychonomic Science, 6*, 69–70.

Angelone, A. & Coulter, N. A. (1964). Respiratory sinus arrhythmia: A frequency dependent phenomenon. *Journal of Applied Physiology, 19*, 479–482.

Ashby, F. G., Isen, A. M., & Turken, U. (1999). A neuropsychological theory of positive affect and its influence on cognition. *Psychological Review, 106*, 529–550.

Ayres, P. (2006). Using subjective measures to detect variations of intrinsic cognitive load within problems. *Learning and Instruction, 16*, 389–400.

Backs, R. W., Lenneman, J. K., Wetzel, J. M., & Green, P. (2003). Cardiac measures of driver workload during simulated driving with and without visual occlusion. *Human Factors, 45*, 525–538.

Backs, R. W., Navidzadeh, T., & Xu, X. (2000). Cardiorespiratory indices of mental workload during simulated air traffic control. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting 2000, 44*, 3-89–3-92.

Backs, R. W., Ryan, A. M., & Wilson, G. F. (1994). Psychophysiological measures of workload during continuous manual performance. *Human Factors, 36*, 514–531.

Backs, R. W. & Seljos, K. A. (1994). Metabolic and cardiorespiratory measures of mental effort: The effects of level of difficulty in a working memory task. *International Journal of Psychophysiology, 16*, 57–68.

Barbosa, D. F., Prada, F. J. A., Glanner, M. F., Nóbrega, O. D. T., & Córdova, C. (2010). Cardiovascular response to Stroop test: Comparison between the computerized and verbal tests. *Arquivos brasileiros de cardiologia, 94*, 507–511.

Barrett, L. F., Quigley, K. S., Bliss-Moreau, E., & Aronson, K. R. (2004). Interoceptive sensitivity and self-reports of emotional experience. *Journal of Personality and Social Psychology*, *87*, 684–697.

Bass, C. & Gardner, W. N. (1985). Emotional influences on breathing and breathlessness. *Journal of Psychosomatic Research, 29*, 599–609.

Beasley, M., Thompson, T., & Davidson, J. (2003). Resilience in response to life stress: The effects of coping style and cognitive hardiness. *Personality and Individual Differences, 34*, 77–95.

Beda, A., Jandre, F. C., Phillips, D. I., Giannella-Neto, A., & Simpson, D. M. (2007). Heart-rate and blood-pressure variability during psychophysiological tasks involving speech: Influence of respiration. *Psychophysiology, 44*, 767–778.

Bernardi, L., Wdowczyk-Szulc, J., Valenti, C., Castoldi, S., Passino, C., Spadacini, G., & Sleight, P. (2000). Effects of controlled breathing, mental activity and mental stress with or without verbalization on heart rate variability. *Journal of the American College of Cardiology, 35*, 1462–1469.

Berntson, G. G., Bigger, J. T., Eckberg, D. L., Grossman, P., Kaufmann, P. G., Malik, M., Nadaraja, H. N., Porges, S. W., Saul, J. P., Stone, P. H., & Van Der Molen, M. W. (1997). Heart rate variability: Origins, methods, and interpretive caveats. *Psychophysiology*, *34*, 623–648.

Bloch, S., Lemeignan, M., & Aguilera-T., N. (1991). Specific respiratory patterns distinguish among human basic emotions. *International Journal of Psychophysiology, 11*, 14–154.

Bloch-Salisbury, E., Lansing, R., & Shea, S. A. (2000). Acute changes in carbon dioxide levels alter the electroencephalogram without affecting cognitive function. *Psychophysiology, 37*, 418–426.

Boiten, F. H. (1998). The effects of emotional behaviour on components of the respiratory cycle. *Biological Psychology, 49*, 29–51.

Boiten, F. H., Frijda, N. H., & Wientjes C. J. E. (1994). Emotions and respiratory patterns: Review and critical analysis. *International Journal of Psychophysiology, 17*, 103–128.

Borkenau, P. & Ostendorf, F. (2008). *NEO-Fünf-Faktoren Inventar (NEO-FFI) nach Costa und McCrae* [NEO Five-Factor Personality Inventory (NEO-FFI) according Costa and McCrae]. Göttingen: Hogrefe.

Boucsein, W., Koglbauer, I., Braunstingl, R., & Kallus, W. (2011). The use of psychophysiological measures during complex flight maneuvers. An expert pilot study. In M. Ouwerkerk, J. H. D. M. Westerink, & M. Krans (Eds.), *Sensing emotions in context: The impact of context on behavioral and physiological experience measurements* (pp. 53–64). Berlin: Springer.

Bradley, M. M. & Lang, P. J. (1994). Measuring emotion: The self-assessment manikin and the semantic differential. *Journal of Behavior Therapy and Experimental Psychiatry*, *25*, 49–59.

Brookings, J. B., Wilson, G. F., & Swain, C. R. (1996). Psychophysiological responses to changes in workload during simulated air traffic control. *Biological Psychology, 42*, 361–377.

Brosschot, J. F., Gerin, W., & Thayer, J. F. (2006). The perseverative cognition hypothesis: A review of worry, prolonged stress-related physiological activation, and health. *Journal of Psychosomatic Research, 60*, 113–124.

Brosschot, J. F. & Thayer, J. F. (2003). Heart rate response is longer after negative emotions than after positive emotions. *International Journal of Psychophysiology, 50*, 181–187.

Brouwer, A.-M., Hogervorst, M. A., Holewijn, M., & van Erp, J. B. F. (2014). Evidence for effects of task difficulty but not learning on neurophysiological variables associated with effort. *International Journal of Psychophysiology, 93*, 242–252.

Bulteel, K., Ceulemans, E., Thompson, R. J., Waugh, C. E., Gotlib, I. H., Tuerlinckx, F., & Kuppens, P. (2014). DeCon: A tool to detect emotional concordance in multivariate time series data of emotional responding. *Biological Psychology*, *98*, 29–42.

Burleson, M. H., Malarkey, W. B., Cacioppo, J. T., Poehlmann, K. M., Kiecolt-Glaser, J. K., Berntson, G. G., & Glaser, R. (1998). Postmenopausal hormone replacement: Effects on autonomic, neuroendocrine, and immune reactivity to brief psychological stressors. *Psychosomatic Medicine, 60*, 17–25.

Buss, D. M. & Scheier, M. F. (1976). Self-consciousness, self-awareness, and self-attribution. *Journal of Research in Personality*, *10*, 463–468.

Cacioppo, J. T., Berntson, G. G., Larsen, J. T., Poehlmann, K. M., & Ito, T. A. (2000). The psychophysiology of emotion. In R. Lewis & J. M. Haviland-Jones (Eds.), *The handbook of emotion* (2nd ed., pp. 173–191). New York: Guilford Press.

Cacioppo, J. T., Rourke, P. A., Marshall-Goodell, B. S., Tassinary, L. G., & Baron, R. S. (1990). Rudimentary physiological effects of mere observation. *Psychophysiology, 27*, 177–186.

Cain, B. (2007). *A review of the mental workload literature*. Report #RTOTR-HFM-121-Part-II. Defence Research and Development Toronto (Canada).

Cardús, J., Burgos, F., Diaz, O., Roca, J., Barberá, J. A., Marrades, R. M., Rodriguez-Roisin, R., & Wagner, P. D. (1997). Increase in pulmonary ventilation–perfusion inequality with age in healthy individuals. *American Journal of Respiratory and Critical Care Medicine, 156*, 648–653.

Carley, W. M. (1999, January 21). *Swissair pilots differed on how to avoid crash.* The Wall Street Journal website. Retrieved from http://www.wsj.com/articles/SB916877132209838000. Accessed March 4, 2015.

Carroll, J. B. (1978). How shall we study individual differences in cognitive abilities?—Methodological and theoretical perspectives. *Intelligence*, *2*, 87–115.

Carroll, J. B. (1993). *Human cognitive abilities: A survey of factor-analytic studies*. Cambridge: Cambridge University Press.

Carroll, J. B. (1995). On methodology in the study of cognitive abilities. *Multivariate Behavioral Research, 30*, 429–452.

Carroll, D., Turner, J. R., & Hellawell, J. C. (1986). Heart rate and oxygen consumption during active psychological challenge: The effects of level of difficulty. *Psychophysiology, 23*, 174–181.

Carver, C. S. & Scheier, M. F. (2011). Self-regulation of action and affect. In K. D. Vohs & R. F. Baumeister (Eds.), *Handbook of self-regulation: Research, theory, and applications* (pp. 3–21). New York: Guilford Press.

Chen, H. I. & Kuo, C. S. (1989). Relationship between respiratory muscle function and age, sex, and other factors. *Journal of Applied Physiology, 66*, 943–948.

Chida, Y. & Hamer, M. (2008). Chronic psychosocial factors and acute physiological responses to laboratory-induced stress in healthy populations: A quantitative review of 30 years of investigations. *Psychological Bulletin, 134*, 829–885.

Cohen, J. (2009). *Statistical power analysis for the behavioral sciences* (2nd ed.). New York: Psychology Press.

Conrad, B. & Schönle, P. (1979). Speech and respiration. *Archiv für Psychiatrie und Nervenkrankheiten, 226*, 251–268.

Craig, A. D. (2002). How do you feel? Interoception: The sense of the physiological condition of the body. *Nature Reviews Neuroscience*, *3*, 655–666.

de Geus, E. J. C., Van Doornen, L. J. P., de Visser, D. C., & Orlebeke, J. F. (1990). Existing and training induced differences in aerobic fitness: Their relationship to physiological response patterns during different types of stress. *Psychophysiology, 27*, 457–477.

de Geus, E. J. C., Willemsen, G. H. M., Klaver, C. H. A. M., & Van Doornen, L. J .P. (1995). Ambulatory assessment of respiratory sinus arrhythmia and respiration rate. *Biological Psychology, 41*, 205–227.

de Visser, D. C., van Hooft, I. M., van Doornen, L. J., Hofman, A., Orlebeke, J. F., & Grobbee, D. E. (1995). Cardiovascular response to mental stress in offspring of hypertensive parents: The Dutch Hypertension and Offspring Study. *Journal of Hypertension, 13*, 901–908.

DeLeeuw, K. E. & Mayer, R. E. (2008). A comparison of three measures of cognitive load: Evidence for separable measures of intrinsic, extraneous, and germane load. *Journal of Educational Psychology, 100*, 223–234.

Delistraty, D. A., Greene, W. A., Carlberg, K. A., & Raver, K. K. (1991). Use of graded exercise to evaluate physiological hyperreactivity to mental stress. *Medicine and Science in Sports and Exercise, 23*, 476–481.

Denver, J. W., Reed, S. F., & Porges, S. W. (2007). Methodological issues in the quantification of respiratory sinus arrhythmia. *Biological Psychology, 74*, 286–294.

Dhokalia, A., Parsons, D. J., & Anderson, D. E. (1998). Resting end-tidal $CO_2$ association with age, gender, and personality. *Psychosomatic Medicine, 60*, 33–37.

Dienstbier, R. A. (1989). Arousal and physiological toughness: Implications for mental and physical health. *Psychological Review, 96*, 84–100.

Dijksterhuis, C., Brookhuis, K. A., & De Waard, D. (2011). Effects of steering demand on lane keeping behaviour, self-reports, and physiology. A simulator study. *Accident Analysis & Prevention, 43*, 1074–1081.

DiStefano, C., Zhu, M., & Mindrila, D. (2009). Understanding and using factor scores: Considerations for the applied researcher. *Practical Assessment, Research & Evaluation, 14*, 1–11.

Dudycha, A. L. & Naylor, J. C. (1966). Characteristics of the human inference process in complex choice behavior situations. *Organizational Behavior and Human Performance, 1*, 110–128.

Durlak. J. A. (2009). How to select, calculate, and interpret effect sizes. *Journal of Pediatric Psychology, 34*, 917–928.

Duschek, S., Muckenthaler, M., Werner, N., & del Paso, G. A. R. (2009). Relationships between features of autonomic cardiovascular control and cognitive performance. *Biological Psychology, 81*, 110–117.

Eggemeier, F. T. & Wilson, G. F. (1991). Performance-based and subjective assessment of workload in multi-task environments. In D. L. Damos (Ed.), *Multiple task performance* (pp. 217–278). London: Taylor & Francis.

Endler, N. S. & Parker, J. D. (1990). Multidimensional assessment of coping: a critical evaluation. *Journal of Personality and Social Psychology, 58*, 844–854.

Endsley, M. R. (1999). Situation awareness in aviation systems. In D. J. Garland, J. A. Wise, and V. D. Hopkin (Eds.), *Handbook of aviation human factors* (pp. 257–276). Mahwah: Lawrence Erlbaum Associates.

Engel, B. T. & Talan, M. I. (1991). Cardiovascular responses as behavior. *Circulation, 83* (4 Suppl), II9–13.

Ernst, J. M., Litvack, D. A., Lozano, D. L., Cacioppo, J. T., & Berntson, G. G. (1999). Impedance pneumography: Noise as signal in impedance cardiography. *Psychophysiology, 36*, 333–338.

Ettema, J. H. & Zielhuis, R. L. (1971). Physiological parameters of mental load. *Ergonomics, 14*, 137–144.

Eysenck, M. W. & Calvo, M. G. (1992). Anxiety and performance: The processing efficiency theory. *Cognition and Emotion, 6*, 409–434.

Eysenck, M. W., Derakshan, N., Santos, R., & Calvo, M. G. (2007). Anxiety and cognitive performance: Attentional control theory. *Emotion, 7*, 336-353.

Faes, L., Porta, A., Cucino, R., Cerutti, S., Antolini, R., & Nollo, G. (2004). Causal transfer function analysis to describe closed loop interactions between cardiovascular and cardiorespiratory variability signals. *Biological Cybernetics, 90*, 390–399.

Fahrenberg, J. (1979). Psychophysiologie [Psychophysiology]. In K. P. Kisker, J. E. Meyer, C. Müller, & E. Strömgren (Eds.), *Psychiatrie der Gegenwart* (2nd ed., pp. 92–210). Berlin: Springer.

Fahrenberg, J., Foerster, F., Schneider, H.-J., Müller, W., & Myrtek, M. (1986). Predictability of individual differences in activation processes in a field setting based on laboratory measures. *Psychophysiology, 23*, 323–333.

Fairclough, S. H., Venables, L., & Tattersall, A. (2005). The influence of task demand and learning on the psychophysiological response. *International Journal of Psychophysiology, 56*, 171–184.

Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods, 39*, 175–191.

Fenigstein, A. (2009). Private and public self-consciousness. In M. R. Leary & R. H. Hoyle (Eds.), *Handbook of individual differences in social behavior* (pp. 495–511). New York: Guilford.

Filipp, S.-H. & Freudenberg, E. (1989). *Fragebogen zur Erfassung dispositionaler Selbstaufmerksamkeit (SAM)* [Questionnaire assessing dispositional self-consciousness (SAM)]. Göttingen: Hogrefe.

Fokkema, D. S. (1999). The psychobiology of strained breathing and its cardiovascular implications: A functional system review. *Psychophysiology, 36*, 164–175.

Fournier, L. R., Wilson, G. F., & Swain, C. R. (1999). Electrophysiological, behavioral, and subjective indexes of workload when performing multiple tasks: Manipulations of task difficulty and training. *International Journal of Psychophysiology, 31*, 129–145.

Fredrickson, B. L. & Branigan, C. (2005). Positive emotions broaden the scope of attention and thought-action repertoires. *Cognition and Emotion, 19*, 313–332.

Friedman, B. H. & Thayer, J. F. (1998). Anxiety and autonomic flexibility: a cardiovascular approach. *Biological Psychology, 47*, 243–263.

Gaillard, A. W. K. (1993). Comparing the concepts of mental load and stress. *Ergonomics, 36*, 991–1005.

Gaillard, A. W. K. & Wientjes, C. J. E. (1994). Mental load and work stress as two types of energy mobilization. *Work & Stress, 8*, 141–152.

Gallego, J., Nsegbe, E., & Durand, E. (2001). Learning in respiratory control. *Behavior Modification, 25*, 495–512.

Galletly, D. C. & Larsen, P. D. (1999). The determination of cardioventilatory coupling from heart rate and ventilatory time series. *Research in Experimental Medicine, 199*, 95–99.

Gibson, T.M. (1978). Effects of hypocapnia on psychomotor and intellectual performance. *Aviation, Space, and Environmental Medicine, 49*, 943–946.

Goeters, K.-M., Maschke, P., & Eißfeldt, H. (2004). Ability requirements in core aviation professions: Job analysis of airline pilots and air traffic controllers. In K.-M. Goeters (Ed.), *Aviation psychology: Practice and research* (pp. 99–119). Aldershot: Ashgate Publishing Limited.

Goldberg, L. R. (1970). Man versus model of man: A rationale, plus some evidence, for a method of improving on clinical inferences. *Psychological Bulletin, 73*, 22–432.

Gomez, P., Stahe, W. A., & Danuser, B. (2004).Respiratory responses during affective picture viewing. *Biological Psychology, 67*, 359–373.

Gomez, R., Holmberg, K., Bounds, J., Fullarton, C., & Gomez, A. (1999). Neuroticism and extraversion as predictors of coping styles during early adolescence. *Personality and Individual Differences, 27*, 3–17.

Gopher, D. & Donchin, E. (1986). Workload: An examination of the concept. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance* (pp. 41-1–41-49). Oxford: John Wiley & Sons.

Grassmann, M., Vlemincx, E., von Leupoldt, A., & Van den Bergh, O. (in press). The role of respiratory measures to assess mental load in pilot selection. *Ergonomics,* doi: 10.1080/00140139.2015.1090019

Grassmann, M., Vlemincx, E., von Leupoldt, A., & Van den Bergh, O. (submitted). Individual differences in cardiorespiratory measures of mental workload: An investigation of negative affectivity and cognitive avoidant coping in pilot candidates.

Grassmann, M., Vlemincx, E., von Leupoldt, A., Mittelstädt, J. M., & Van den Bergh, O. (submitted). Respiratory changes in response to cognitive load: A systematic review.

Green, R. G., Muir, H., James, M., Gradwell, D., & Green, R. L. (2005). *Human factors for pilots* ($2^{nd}$ ed.). Farnham: Ashgate Publishing.

Grossman, P., Karemaker, J., & Wieling, W. (1991). Prediction of tonic parasympathetic cardiac control using respiratory sinus arrhythmia: The need for respiratory control. *Psychophysiology*, *28*, 201–216.

Grossman, P., Stemmler, G., & Meinhardt, E. (1990). Paced respiratory sinus arrhythmia as an index of cardiac parasympathetic tone during varying behavioral tasks. *Psychophysiology, 27*, 404–416.

Grossman, P. & Taylor, E. W. (2007). Toward understanding respiratory sinus arrhythmia: Relations to cardiac vagal tone, evolution and biobehavioral functions. *Biological Psychology, 74*, 263–285.

Grossman, P. & Wientjes, C. J. E. (1989). Respiratory disorders: Asthma and hyperventilation syndrome. In G. Turpin (Ed.), *Handbook of clinical psychophysiology* (pp. 519–554). Chichester: Wiley.

Grossman, P. & Wientjes, C. J. (2001). How breathing adjusts to mental and physical demands. In Y. Haruki, I. Homma, A. Umezawa, & Y. Masaoka (Eds.), *Respiration and emotion* (pp. 43–54). Tokyo: Springer.

Hansen, A.L., Johnsen, B.H., & Thayer, J. (2003). Vagal influence on working memory and attention. *International Journal of Psychophysiology, 48*, 263–274.

Harding, R. M. (1987). *Human respiratory responses during high performance flight*. AGARDograph No. 312W, NATO Advisory Group for Aerospace Research and Development (pp. 1–83).

Harris, D. (2011). *Human performance on the flight deck*. Farnham: Ashgate Publishing.

Hart, S. G. & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. *Advances in Psychology*, *52*, 139–183.

Hasan, A. (2009). *Handbook of blood gas/acid-base interpretation*. London: Springer.

Herbert, B. M., Pollatos, O., Flor, H., Enck, P., & Schandry, R. (2010). Cardiac awareness and autonomic cardiac reactivity during emotional picture viewing and mental stress. *Psychophysiology, 47*, 342–354.

Hida, W., Kikuchi, Y., Okabe, S., Miki, H., Kurosawa, H., & Shirato, K. (1996). $CO_2$ response for the brain stem artery blood flow velocity in man. *Respiration Physiology, 104*, 71–75.

Higgins, E. T. (2000). Does personality provide unique explanations for behaviour? Personality as cross-person variability in general principles. *European Journal of Personality, 14*, 391–406.

Hockey, G. R. J. (1986). A state control theory of adaptation to stress and individual differences in stress management. In G. R. J. Hockey, A. W. K. Gaillard, & M. G. H. Coles (Eds.), *Energetics and human information processing* (pp. 285–298). Dordrecht: Martinus Nijhoff.

Hoffman, P. J. (1960). The paramorphic representation of clinical judgment. *Psychological Bulletin, 57*, 116–131.

Holm, S. (1979). A Simple sequentially rejective multiple test procedure. *Scandinavian Journal of Statistics, 6*, 65–70.

Hoshikawa, Y. & Yamamoto, Y. (1997). Effects of Stroop color-word conflict test on the autonomic nervous system responses. *American Journal of Physiology – Heart and Circulatory Physiology, 272*, H1113–H1121.

Houtveen, J. H., Groot, P. F., & de Geus, E. J. C. (2006). Validation of the thoracic impedance derived respiratory signal using multilevel analysis. *International Journal of Psychophysiology, 59*, 97–106.

Houtveen, J. H., Rietveld, S., & De Geus, E. J. (2002). Contribution of tonic vagal modulation of heart rate, central respiratory drive, respiratory depth, and respiratory frequency to respiratory sinus arrhythmia during mental stress and physical exercise. *Psychophysiology, 39*, 427–436.

Huey, F. M. & Wickens, C. D. (1993). *Workload transition: Implications for individual and team performance*. Washington: National Academy Press.

Humphreys, M. S. & Revelle, W. (1984). Personality, motivation and performance: A theory of the relationship between individual differences and information processing. *Psychological Review, 91*, 153–184.

Izard, C. E., Libero, D. Z., Putnam, P., & Haynes, O. M. (1993). Stability of emotion experiences and their relations to traits of personality. *Journal of Personality and Social Psychology, 64*, 847–860.

Jennings, J. R., Kamarck, T., Stewart, C., Eddy, M., & Johnson, P. (1992). Alternate cardiovascular baseline techniques: Vanilla or resting baseline. *Psychophysiology, 29*, 742–750.

Jennings, J. R. & Wood, C. C. (1977). Cardiac cycle time effects on performance, phasic cardiac responses and their intercorrelation in choice reaction time. *Psychophysiology, 14*, 297–307.

Jerusalem, M. & Schwarzer, R. (1992). Self-efficacy as a resource factor in stress appraisal processes. In R. Schwarzer (Ed.), *Self-efficacy: Thought control of action* (pp. 195–213). Washington: Hemisphere Publishing.

Jorna, P. G. A. M. (1993). Heart rate and workload variations in actual and simulated flight. *Ergonomics, 36*, 1043–1054.

Kagan, J. & Rosman, B. L. (1964). Cardiac and respiratory correlates of attention and an analytic attitude. *Journal of Experimental Child Psychology, 1*, 50–63.

Kantowitz, B. H. (1987). Mental workload. In P. A. Hancock (Ed.), *Human factors psychology* (pp. 81–121). Amsterdam: Elsevier.

Karavidas, M. K., Lehrer, P. M., Lu, S. E., Vaschillo, E., Vaschillo, B., & Cheng, A. (2010). The effects of workload on respiratory variables in simulated flight: A preliminary study. *Biological Psychology, 84*, 157–160.

Karwowski, W., Cuevas, H. M., Weaver, J. L., Matthews, G., Gielo-Perezak, K., Hettinger, L., & Hancock, P. A. (2003). *Considering the importance of individual differences in human factors research: No longer simply confounding noise*. Panel presented at the 47th annual meeting of the Human Factors and Ergonomics Society.

Kashdan, T. B. & Rottenberg, J. (2010). Psychological flexibility as a fundamental aspect of health. *Clinical Psychology Review, 30*, 865–878.

Kaufmann, T., Sütterlin, S., Schulz, S. M., & Vögele, C. (2011). ARTiiFACT: A tool for heart rate artifact processing and heart rate variability analysis. *Behavior Research Methods, 43*, 1161–1170.

Kazdin, A. E. (1977). Artifact, bias, and complexity of assessment: The ABCs of reliability. *Journal of Applied Behavior Analysis, 10*, 141–150.

King, A. C., Taylor, C. B., Albright, C. A., & Haskell, W. L. (1990). The relationship between repressive and defensive coping styles and blood pressure responses in healthy, middle-aged men and women. *Journal of Psychosomatic Research, 34*, 461–471.

Kodesh, E. & Kizony, R. (2014). Measuring cardiopulmonary parameters during dual-task while walking. *Journal of Basic and Clinical Physiology and Pharmacology, 25*, 155–160.

Kohlmann, C. W., Weidner, G., & Messina, C. R. (1996). Avoidant coping style and verbal-cardiovascular response dissociation. *Psychology and Health, 11*, 371–384.

Kramer, A. F. (1991). Physiological metrics of mental workload: A review of recent progress. In D. L. Damos (Ed.), *Multiple task performance* (pp. 279–328). London: Taylor & Francis.

Kreibig, S. D. (2010). Autonomic nervous system activity in emotion: A review. *Biological Psychology, 84*, 394–421.

Krohne, H. W. (1996). Individual differences in coping. In M. Zeidner & N. S. Endler (Eds.), *Handbook of coping: Theory, research, applications* (pp. 381–409). Oxford: John Wiley & Sons.

Krohne, H. W. & Egloff, B. (1999). *Das Angstbewältigungs-Inventar (ABI)* [Mainz Coping Inventory (MCI)]. Mainz: Swets Test Service.

Krohne, H. W., Egloff, B., Varner, L. J., Burns, L. R., Weidner, G., & Ellis, H. C. (2000). The assessment of dispositional vigilance and cognitive avoidance: Factorial structure, psychometric properties, and validity of the Mainz Coping Inventory. *Cognitive Therapy and Research*, *24*, 297–311.

Kuehl, L. K., Deuter, C. E., Richter, S., Schulz, A., Rueddel, H., & Schaechinger, H. (2015). Two separable mechanisms are responsible for mental stress effects on high frequency heart rate variability: An intra-individual approach in a healthy and a diabetic sample. *International Journal of Psychophysiology, 95*, 299–303.

Lacey, J. L. (1967). Somatic response patterning and stress: Some revisions of activation theory. In M. H. Appley & R. Trumbull (Eds.), *Psychological stress: Issues in research* (pp. 14–42). New York: Appleton-Century-Crofts.

Lacey, J. L., Bateman, D. E., & Van Lehn, R. (1953). Autonomic response specificity: An experimental study. *Psychosomatic Medicine, 15*, 8–21.

Lackner, H. K., Goswami, N., Hinghofer-Szalkay, H., Papousek, I., Scharfetter, H., Furian, R., & Schwaberger, G. (2010). Effects of stimuli on cardiovascular reactivity occurring at regular intervals during mental stress. *Journal of Psychophysiology, 24*, 48–60.

Laux, L., Glanzmann, P., Schaffner, P., & Spielberger, C.D. (1981). *Das State-Trait-Angstinventar* [State-Trait-Anxiety-Inventory (STAI)]. Weinheim: Beltz.

Lazarus, R. S. & Folkman, S. (1984). *Stress, appraisal, and coping*. New York: Springer.

Lehrer, P., Karavidas, M., Lu, S. E., Vaschillo, E., Vaschillo, B., & Cheng, A. (2010). Cardiac data increase association between self-report and both expert ratings of task load and task performance in flight simulator tasks: An exploratory study. *International Journal of Psychophysiology*, *76*, 80–87.

Lewis, G. F., Furman, S. A., McCool, M. F., & Porges, S. W. (2012). Statistical strategies to quantify respiratory sinus arrhythmia: Are commonly used metrics equivalent? *Biological Psychology*, *89,* 349–364.

Light, K. C. & Obrist, P. A. (1980). Cardiovascular response to stress: Effects of opportunity to avoid, shock experience, and performance feedback. *Psychophysiology, 17*, 243–252.

Lipsey, M. W. & Wilson, D. B. (2001). *Practical meta-analysis* (Vol. 49). Thousand Oaks: Sage publications.

Lovallo, W. R. & Gerin, W. (2003). Psychophysiological reactivity: Mechanisms and pathways to cardiovascular disease. *Psychosomatic Medicine, 65*, 36–45.

Malmo, R. B. (1965). Physiological gradients and behavior. *Psychological Bulletin, 664*, 225–234.

Manuck, S. B., Kamarck, T. W., Kasprowicz, A. S., & Waldstein, S. R. (1993). Stability and patterning of behaviorally evoked cardiovascular reactivity. In J. J. Blascovic & E. S. Katkin (Eds.), *Cardiovascular reactivity to psychological stress* & *disease* (pp. 111–134). Washington: American Psychological Association.

Manuck, S. B. & Garland, F. N. (1980). Stability of individual differences in cardiovascular reactivity: A thirteen month follow-up. *Physiology* & *Behavior, 24*, 621–624.

Manzey, D. (1998). Psychophysiologie mentaler Beanspruchung [Psychophysiology of mental strain]. In F. Rösler (Ed.), *Enzyklopädie der Psychologie. Ergebnisse und Anwendungen der Psychophysiologie* (pp. 799–864). Göttingen: Hogrefe.

Marangoni, A. H. & Hurford, D. P. (1990). The effect of varying alveolar carbon dioxide levels on free recall. *Brain and Cognition, 13*, 77–85.

Marwitz, M. & Stemmler, G. (1998). On the status of individual response specificity. *Psychophysiology, 35*, 1–15.

Masaoka, Y. & Homma, I. (1997). Anxiety and respiratory patterns: their relationship during mental stress and physical load. *International Journal of Psychophysiology, 27*, 153–159.

Masaoka, Y. & Homma, I. (1999). Expiratory time determined by individual anxiety levels in humans. *Journal of Applied Physiology, 86*, 1329–1336.

Mathewson, K. J., Jetha, M. K., Drmic, I. E., Bryson, S. E., Goldberg, J. O., Hall, G. B., Santesso, D. L., Segalowitz, S. J., & Schmidt, L. A. (2010). Autonomic predictors of Stroop performance in young and middle-aged adults. *International Journal of Psychophysiology, 76*, 123–129.

Matthews, G. & Davies, D. R. (2001). Individual differences in energetic arousal and sustained attention: A dual-task study. *Personality and Individual Differences, 31*, 575–589.

Matthews, G., Deary, I. J., & Whiteman, M. C. (2003). *Personality traits*. Cambridge: Cambridge University Press.

Matthews, G., Warm, J. S., Reinerman-Jones, L. E., Langheim, L. K.,Washburn, D. A., & Tripp, L. (2010). Task engagement, cerebral blood flow velocity, and diagnostic monitoring for sustained attention. *Applied Journal of Experimental Psychology, 16*, 187–203.

McCarthy, D., Corban, R., Legg, S., & Faris, J. (1995). Effects of mild hypoxia on perceptual-motor performance: A signal-detection approach. *Ergonomics, 38*, 1979–1992.

Mehler, B., Reimer, B., Coughlin, J. F., & Dusek, J. A. (2009). Impact of incremental increases in cognitive workload on physiological arousal and performance in young adult drivers. *Transportation Research Record: Journal of the Transportation Research Board, 2138*, 6–12.

Melis, C. & van Boxtel, A. (2007). Autonomic physiological response patterns related to intelligence. *Intelligence, 35*, 471–487.

Mischel, W. & Shoda. Y. (1995). A cognitive-affective system theory of personality: Reconceptualizing situations, dispositions, dynamics, and invariance in personality structure. *Psychological Review, 102*, 246–268.

Miyake, S. (2001). Multivariate workload evaluation combining physiological and subjective measures. *International Journal of Psychophysiology*, *40*, 233–238.

Miyake, S., Yamada, S., Shoji, T., Takae, Y., Kuge, N., & Yamamura, T. (2009). Physiological responses to workload change. A test/retest examination. *Applied Ergonomics, 40*, 987–996.

Moher, D., Liberati, A., Tetzlaff, J., & Altman, D. G. (2009). Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement. *Annals of Internal Medicine*, *151*, 264–269.

Moray, N. (1982). Subjective mental workload. *Human Factors*, *24*, 25–40.

Morris, C. H. & Leung, Y. K. (2006). Pilot mental workload: How well do pilots really perform? *Ergonomics, 49*, 1581–1596.

Mrowka, R., Patzak, A., & Rosenblum, M. (2000). Quantitative analysis of cardiorespiratory synchronization in infants. *International Journal of Bifurcation and Chaos, 10*, 2479–2488.

Mulder, G. & Mulder, L. J. M. (1981). Information processing and cardiovascular control. *Psychophysiology, 14*, 392–402.

Muth, E. R., Moss, J. D., Rosopa, P. J., Salley, J. N., & Walker, A. D. (2012). Respiratory sinus arrhythmia as a measure of cognitive workload. *International Journal of Psychophysiology*, *83*, 96–101.

Myrtek, M. (1998). Metaanalysen zur psychophysiologischen Persönlichkeitsforschung [Meta-analyses on psychophysiological personality research]. In F. Rösler (Ed.), *Enzyklopädie der Psychologie. Serie I Biologische Psychologie. Bereich Theorie und Forschung. Bd 5: Ergebnisse und Anwendungen der Psychophysiologie* (pp. 285–344). Göttingen: Hogrefe.

Newton, T. L. & Contrada, R. J. (1992). Repressive coping and verbal-autonomic response dissociation: The influence of social context. *Journal of Personality and Social Psychology*, *62*, 159–167.

Niizeki, K. & Saitoh, T. (2012). Incoherent oscillations of respiratory sinus arrhythmia during acute mental stress in humans. *American Journal of Physiology – Heart and Circulatory Physiology, 302*, H359–H367.

Nilsen, K. B., Sand, T., Stovner, L. J., Leistad, R. B., & Westgaard, R. H. (2007). Autonomic and muscular responses and recovery to one-hour laboratory mental stress in healthy subjects. *BMC Musculoskeletal Disorders, 8*, 81.

Novak, D., Mihelj, M., & Munih, M. (2012). Dual-task performance in multimodal human-computer interaction: A psychophysiological perspective. *Multimedia Tools and Applications, 56*, 553–567.

Obrist, P. A., Howard, J. L., Lawler, J. E., Galosy, R. A., Meyers, K. A., & Gaebelein, C. J. (1974). The cardiac-somatic interaction. In P. A. Obrist, A. H. Black, J. Brener, & L. V. DiCara (Eds.), *Cardiovascular psychophysiology: Current issues in response mechanisms, biofeedback and methodology* (pp. 136–162). Chicago: Aldine.

O'Donnell, R. D. & Eggemeier, F. T. (1986). Workload assessment methodology. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. II. Cognitive processes and performance* (pp. 42-1–42-49). New York: Wiley.

Ottaviani, C., Thayer, J. F., Verkuil, B., Lonigro, A., Medea, B., Couyoumdjian, A., & Brosschot, J. F. (2015). Physiological concomitants of perseverative cognition: A systematic review and meta-analysis. *Psychological Bulletin*, doi: 10.1037/bul0000036

Overbeek, T. J. M., van Boxtel, A., & Westerink, J. H. D. M. (2014). Respiratory sinus arrhythmia responses to cognitive tasks: Effects of task factors and RSA indices. *Biological Psychology, 99*, 1–14.

Papadelis, C., Kourtidou-Papadeli, C., Bamidis, P., & Albani, M. (2007). Effects of imagery training on cognitive performance and use of physiological measures as an assessment tool of mental effort. *Brain and Cognition, 64*, 74–85.

Park, G., Vasey, M., Van Bavel, J. J., & Thayer, J. F. (2014). When tonic cardiac vagal tone predicts changes in phasic vagal tone: The role of fear and perceptual load. *Psychophysiology, 51*, 419–426.

Pattyn, N., Migeotte, P.-F., Neyt, X., van den Nest, A., & Cluydts, R. (2010). Comparing real-life and laboratory-induced stress reactivity on cardio-respiratory parameters: Differentiation of a tonic and a phasic component. *Physiology & Behavior, 101*, 218–223.

Pattyn, N., Neyt, X., Henderickx, D., & Soetens, E. (2008). Psychophysiological investigation of vigilance decrement: Boredom or cognitive fatigue? *Physiology & Behavior, 93*, 369–378.

Pawar, T., Anantakrishnan, N. S., Chaudhuri, S., & Duttagupta, S. P. (2007). Impact analysis of body movement in ambulatory ECG. *Proceedings of the 29th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 5453–5456.

Perez, W. & Tobin, M. J. (1985). Separation of factors responsible for change in breathing pattern induced by instrumentation. *Journal of Applied Physiology, 59*, 1515–1520.

Phan, C. Q., Tremper, K. K., Lee, S. E., & Barker, S. J. (1987). Noninvasive monitoring of carbon dioxide: A comparison of the partial pressure of transcutaneous and end-tidal carbon dioxide with the partial pressure of arterial carbon dioxide. *Journal of Clinical Monitoring, 3*, 149–154.

Piferi, R. L., Kline, K. A., Younger, J., & Lawler, K. A. (2000). An alternative approach for achieving cardiovascular baseline: Viewing an aquatic video. *International Journal of Psychophysiology, 37*, 207–217.

Porges, S. W. & Byrne, E. A (1992). Research methods for measurement of heart rate and respiration. *Biological Psychology, 34*, 93–130.

Pruneti, C. A. & Boem, A. (1995). Physiological response in healthy subjects and in patients after myocardial infarction, elicited by a new computerised version of the Raven Coloured PM 47 as a mental stress test. *Functional Neurology, 10*, 195–201.

Qu, M., Zhang, Y., Webster, J. G., & Tompkins, W. J. (1986). Motion artifact from spot and band electrodes during impedance cardiography. *IEEE Transactions on Biomedical Engineering, 11*, 1029–1036.

Rahn, H., Otis, M. H., Epstein, M. A., Hunter, S. W., & Fenn, W. O. (1946).The effects of hypocapnia on performance. *Journal of Aviation Medicine, 16*, 164–172.

Roman-Liu, D., Grabarek, I., Bartuzi, P., & Choromański, W. (2013). The influence of mental load on muscle tension. *Ergonomics, 56*, 1125–1133.

Roscoe, A. H. (1993). Heart rate as a psychophysiological measure for in-flight workload assessment. *Ergonomics, 36*, 1055–1062.

Rosenblum, M. G., Cimponeriu, L., Bezerianos, A., Patzak, A., & Mrowka, R. (2002). Identification of coupling direction: Application to cardiorespiratory interaction. *Physical Review E, 65*, 041909.

Roy, M. & Steptoe, A. (1991). The inhibition of cardiovascular responses to mental stress following aerobic exercise. *Psychophysiology, 28*, 689–700.

Rutledge, T. & Linden, W. (2003). Defensiveness and 3-year blood pressure levels among young adults: the mediating effect of stress-reactivity. *Annals of Behavioral Medicine*, *25*, 34–40.

Ryu, K. & Myung, R. (2005). Evaluation of mental workload with a combined measure based on physiological indices during a dual task of tracking and mental arithmetic. *International Journal of Industrial Ergonomics, 35*, 991–1009.

Salvendy, G. (2012). *Handbook of human factors and ergonomics* (4th ed.). Hoboken: John Wiley & Sons.

Saus, E., Johnsen, B. H., Eid, J., & Thayer, J. (2012). Who benefits from simulator training: Personality and heart rate variability in relation to situation awareness during navigation training. *Computers in Human Behavior, 28*, 1262–1268.

Scheier, M. F. & Carver, C. S. (1983). Self-directed attention and the comparison of self with standards. *Journal of Experimental Social Psychology, 19*, 205–222.

Schleifer, L. M., Spalding, T. W., Kerick, S. E., Cram, J. R., Ley, R., & Hatfield, B. D. (2008). Mental stress and trapezius muscle activation under psychomotor challenge: A focus on EMG gaps during computer work. *Psychophysiology, 45*, 356–365.

Schneider, T. R. (2004). The role of neuroticism on psychological and physiological stress responses. *Journal of Experimental Social Psychology, 40*, 795–804.

Schwebel, D. C. & Suls, J., (1999). Cardiovascular reactivity and neuroticism: Results from a laboratory and controlled ambulatory stress protocol. *Journal of Personality, 67*, 67–92.

Schwerdtfeger, A. R. & Rathner, E. M. (in press). The Ecological Validity of the Autonomic-Subjective Response Dissociation in Repressive Coping. *Anxiety, Stress, & Coping,* doi:10.1080/10615806.2015.1048237

Schwerdtfeger, A., Schmukle, S. C., & Egloff, B. (2005). Interactive effects of avoidant coping and parental hypertension on rate pressure product reactivity in women. *Annals of Behavioral Medicine*, *29*, 106–115.

Schwerdtfeger, A., Schmukle, S. C., & Egloff, B. (2006). Verbal-autonomic response dissociations as traits? *Biological Psychology*, *72*, 213–221.

Seery, M. D. (2011). Challenge or threat? Cardiovascular indexes of resilience and vulnerability to potential stress in humans. *Neuroscience & Biobehavioral Reviews*, *35*, 1603–1610.

Seery, M. D. (2013). The biopsychosocial model of challenge and threat: Using the heart to measure the mind. *Social and Personality Psychology Compass*, *7*, 637–653.

Segerstrom, S. C. & Nes, L. S. (2007). Heart rate variability reflects self-regulatory strength, effort, and fatigue. *Psychological Science, 18*, 275–281.

Silvia, P. J., Eddington, K. M., Beaty, R. E., Nusbaum, E. C., & Kwapil, T. R. (2013). Gritty people try harder: Grit and effort-related cardiac autonomic activity during an active coping challenge. *International Journal of Psychophysiology, 88*, 200–205.

Silvia, P. J., Jones, H. C., Kelly, C. S., & Zibaie, A. (2011). Trait self-focused attention, task difficulty, and effort-related cardiovascular reactivity. *International Journal of Psychophysiology*, *79*, 335–340.

Silvia, P. J., Kelly, C. S., Zibaie, A., Nardello, J. L., & Moore, L. C. (2013). Trait self-focused attention increases sensitivity to nonconscious primes: Evidence from effort-related cardiovascular reactivity. *International Journal of Psychophysiology*, *88*, 143–148.

Sloan, R. P., Korten, J. B., & Myers, M. M. (1991). Components of heart rate reactivity during mental arithmetic with and without speaking. *Physiology & Behavior, 50*, 1039–1045.

Sloan, R. P., Shapiro, P. A., Bagiella, E., Fishkin, P. E., Gorman, J. M., & Myers, M. M. (1995). Consistency of heart rate and sympathovagal reactivity across different autonomic contexts. *Psychophysiology, 32*, 452–459.

Sonderegger, A. & Sauer, J. (2009). The influence of laboratory set-up in usability tests: effects on user performance, subjective ratings and physiological measures. *Ergonomics, 52*, 1350–1361.

Song, H. S. & Lehrer, P. M. (2003). The effects of specific respiratory rates on heart rate and heart rate variability. *Applied Psychophysiology and Biofeedback, 28*, 13–23.

Spector, P. E. (2012). Self-Reports for Employee Selection. In N. Schmitt (Ed.), *The Oxford handbook of personnel assessment and selection* (pp. 443–461). New York: Oxford University Press.

Stegen, K., De Bruyne, K., Rasschaert, W., Van de Woestijne, K. P., & Van den Bergh, O. (1999). Fear-relevant images as conditioned stimuli for somatic complaints, respiratory behavior, and reduced end-tidal $pCO_2$. *Journal of Abnormal Psychology, 108*, 143–152.

Stemmler, G. (1997). Selective activation of traits: Boundary conditions for the activation of anger. *Personality and Individual Differences, 22*, 213–233.

Stemmler, G. (2004). Physiological processes during emotion. In P. Philippot & R. S. Feldman (Eds.), *The regulation of emotion* (pp. 33–70). Mahwah: Erlbaum.

Stemmler, G. & Wacker, J. (2010). Personality, emotion, and individual differences in physiological responses. *Biological Psychology, 84*, 541–551.

Steptoe, A., Evans, O., & Fieldman, G. (1997). Perceptions of control over work: Psychophysiological responses to self-paced and externally-paced tasks in an adult population sample. *International Journal of Psychophysiology, 25*, 211–220.

Steptoe, A., Fieldman, G., Evans, O., & Perry, L. (1996). Cardiovascular risk and responsivity to mental stress: The influence of age, gender and risk factors. *Journal of Cardiovascular Risk, 3*, 83–93.

Stöber, J. (1995). Besorgnis: Ein Vergleich dreier Inventare zur Erfassung allgemeiner Sorgen [Worrying: A comparison of three questionnaires concerning everyday worries]. *Zeitschrift für Differentielle und Diagnostische Psychologie, 16*, 50–63.

Suess, W. M., Alexander, A. B., Smith, D. D., Sweeney, H. W., & Marion, R. J. (1980). The effects of psychological stress on respiration: A preliminary study of anxiety and hyperventilation. *Psychophysiology, 17*, 535–540.

Suls, J. & Fletcher, B. (1985). The relative efficacy of avoidant and nonavoidant coping strategies: A meta-analysis. *Health Psychology*, *4*, 249–288.

Svensson, E., Angelborg-Thanderz, M., Sjöberg, L., & Olsson, S. (1997). Information complexity – Mental workload and performance in combat aircraft. *Ergonomics, 40*, 362–380.

Szalma, J. L. (2009). Individual differences in human–technology interaction: Incorporating variation in human characteristics into human factors and ergonomics research and design. *Theoretical Issues in Ergonomics Science*, *10*, 381–397.

Szymura, B. & Wodniecka, Z. (2003). What really bothers neurotics? In search for factors impairing attentional performance. *Personality and Individual Differences, 34*, 109-126.

Takano, Y., Sakamoto, O., Kiyofuji, C., & Ito, K. (2003). A comparison of the end-tidal $CO_2$ measured by portable capnometer and the arterial $pCO_2$ in spontaneously breathing patients. *Respiratory Medicine, 97*, 476–481.

Thayer, R. E. (1978). Toward a psychological theory of multidimensional activation (arousal). *Motivation and Emotion, 2*, 1–34.

Thayer, R. E. (1989). *The biopsychology of mood and arousal*. New York: Oxford University Press.

Thayer, J. F., Hansen, A. L., Saus-Rose, E., & Johnsen, B. H. (2009). Heart rate variability, prefrontal neural function and cognitive performance: The neurovisceral integration perspective on self-regulation, adaptation and health. *Annals of Behavioral Medicine, 37*, 141–153.

Tobin, M. J., Mador, M. J., Guenther, S. M., Lodato, R. F., & Sackner, M. A. (1988). Variability of resting respiratory drive and timing in healthy subjects. *Journal of Applied Physiology, 65*, 309–317.

Tobin, M. J., Perez, W., Guenther, S. M., D'Alonzo, G., & Dantzker, D. R. (1986). Breathing pattern and metabolic behavior during anticipation of exercise. *Journal of Applied Physiology, 60*, 1306–1312.

Tobin, M. J., Yang, K. L., Jubran, A., & Lodato, R. F. (1995). Interrelationship of breath components in neighboring breaths of normal eupnic subjects. *American Journal of Respiratory and Critical Care Medicine, 152*, 1967–1976.

Tomaka, J. & Blascovich, J. (1994). Effects of justice beliefs on cognitive appraisal of and subjective physiological, and behavioral responses to potential stress. *Journal of Personality and Social Psychology*, *67*, 732–740.

Troubat, N., Fargeas-Gluck, M.-A., Tulppo, M., & Dugue, B. (2009). The stress of chess players as a model to study the effects of psychological stimuli on physiological responses: An example of substrate oxidation and heart rate variability in man. *European Journal of Applied Physiology, 105*, 343–349.

Tulga, M. K. (1978). *Dynamic decision making in multitask supervisory control: Comparison of an optimal algorithm to human behavior.* Cambridge: MIT Man Machine Systems Laboratory.

Turner, J. R. (1989). Individual differences in heart rate response during behavioral challenge. *Psychophysiology, 26*, 497–505.

Turner, J. R. & Carroll, D. (1985). Heart rate and oxygen consumption during mental arithmetic, a video game and graded exercise: Further evidence of metabolically-exaggerated cardiac adjustment? *Psychophysiology, 22*, 261–267.

Van den Bergh, O., Zaman, J., Bresseleers, J., Verhamme, P., & Van Diest, I. (2013). Anxiety, pCO2 and cerebral blood flow. *International Journal of Psychophysiology, 89*, 72–77.

Van Diest, I., Janssens, T., Bogaerts, K., Fannes, S., Davenport, P., & Van den Bergh, O. (2009). Affective modulation of inspiratory motor drive. *Psychophysiology, 46*, 12–16.

Van Diest, I., Stegen, K., Van de Woestijne, K. P., Schippers, N., & Van den Bergh, O. (2000). Hyperventilation and attention: Effects of hypocapnia on performance in a Stroop task. *Biological Psychology, 53*, 133–252.

Van Diest, I., Stegen, K., Van de Woestijne, K. P., & Van den Bergh, O. (1999). Critical conditions for respiratory stress responses: A literature review. [In Dutch.] *Gedrag & Gezondheid, 27*, 290–303.

Van Diest, I., Thayer, J. F., Vandeputte, B., Van de Woestijne, K. P., & Van den Bergh, O. (2006). Anxiety and Respiratory Variability. *Physiology & Behavior, 89*, 189–195.

Van Diest, I., Vuerstaek, S., Corne, I., De Peuter, S., Devriese, S., Van de Woestijne, K. P., & Van den Bergh, O. (2003). Resting end-tidal CO2 and negative affectivity. *Psychosomatic Medicine, 65*, 976–983.

Van Diest, I., Winters, W., Devriese, S., Vercamst, E., Han, J. N., Van de Woestijne, K. P., & Van den Bergh, O. (2001). Hyperventilation beyond fight/flight: Respiratory responses during emotional imagery. *Psychophysiology, 38*, 961–968.

Veltman, J. A. (2002). A comparative study of psychophysiological reactions during simulator and real flight. *The International Journal of Aviation Psychology, 12*, 33–48.

Veltman, J. A. & Gaillard, A. W. K. (1996). Physiological indices of workload in a simulated flight task. *Biological Psychology, 42*, 323–342.

Veltman, J. A. & Gaillard, A. W. K. (1998). Physiological workload reactions to increasing levels of task difficulty. *Ergonomics, 41*, 656–669.

Verwey, W. B. & Veltman, H. A. (1996). Detecting short periods of elevated workload: A comparison of nine workload assessment techniques. *Journal of Experimental Psychology: Applied, 2*, 270–285.

Vincente, K. J., Thornton, D. C., & Moray, N. (1987). Spectral analysis of sinus arrhythmia: A measure of mental effort. *Human Factors, 29*, 171–182.

Vlemincx, E., Abelson, J. L., Lehrer, P. M., Davenport, P. W., Van Diest, I., & Van den Bergh, O. (2013). Respiratory variability and sighing: A psychophysiological reset model. *Biological Psychology*, *93*, 24–32.

Vlemincx, E., Taelman, J., De Peuter, S., Van Diest, I., & Van den Bergh, O. (2011). Sigh rate and respiratory variability during mental load and sustained attention. *Psychophysiology, 48*, 117–120.

Vlemincx, E., Van Diest, I., Lehrer, P. M., Aubert, A. E., & Van den Bergh, O. (2010). Respiratory variability preceding and following sighs: A resetter hypothesis. *Biological Psychology, 84*, 82–87.

Vlemincx, E., Van Diest, I., & Van den Bergh, O. (2012). A sigh following sustained attention and mental stress: Effects on respiratory variability. *Physiology & Behavior, 107*, 1–6.

Vlemincx, E., Van Diest, I., & Van den Bergh, O. (2015). Emotion, sighing, and respiratory variability. *Psychophysiology, 52*, 657–666.

Vlemincx, E., Vigo, D., Vansteenwegen, D., Van den Bergh, O., & Van Diest, I. (2013). Do not worry, be mindful: Effects of induced worry and mindfulness on respiratory variability in a nonanxious population. *International Journal of Psychophysiology, 87*, 147–151.

Vögele, C. & Steptoe, A. (1992). Emotional coping and tonic blood pressure as determinants of cardiovascular responses to mental stress. *Journal of Hypertension, 10*, 1079–1087.

von Collani, G. & Herzberg, P. Y. (2003). Eine revidierte Fassung der deutschsprachigen Skala zum Selbstwertgefühl von Rosenberg [A revised German version of the Rosenberg self-esteem scale]. *Zeitschrift für Differentielle und Diagnostische Psychologie, 24*, 3–7.

Weinberger, D. A., Schwartz, G. E., & Davidson, R. J. (1979). Low-anxious, high-anxious, and repressive coping styles: Psychometric patterns and behavioral and physiological responses to stress. *Journal of Abnormal Psychology, 88*, 369–380.

Wenger, M. A., Clemens, T. L., Coleman, D. R., Cullen, T. D., & Engel, B. T. (1961). Autonomic response specificity. *Psychosomatic Medicine, 23*, 185–193.

Wetzel, J. M., Quigley, K. S., Morell, J., Eves, E., & Backs, R. W. (2006). Cardiovascular measures of attention to illusory and nonillusory visual stimuli. *Journal of Psychophysiology, 20*, 276–285.

White, D. P., Douglas, N. J., Pickett, C. K., Weil, J. V., & Zwillich, C. W. (1983). Sexual influence on the control of breathing. *Journal of Applied Physiology, 54*, 874–879.

Wientjes, C. J. E. (1992). Respiration in psychophysiology: Measurement issues and applications. *Biological Psychology, 34*, 179–203.

Wientjes, C. J. E., Gaillard, A. W. K., & ter Maat, R. (1996). Measurement of transcutaneous $pCO_2$ among air traffic controllers: Differential responding to workload and stress. *Biological Psychology, 43*, 250–251.

Wientjes, C. J. E. & Grossman, P. (1994). Overreactivity of the psyche or the soma? Interindividual associations between psychosomatic symptoms, anxiety, heart rate, and end-tidal partial carbon dioxide pressure. *Psychosomatic Medicine, 56*, 533–540.

Wientjes, C. J. E., Grossman, P., & Gaillard, A. W. K. (1998). Influence of drive and timing mechanisms on breathing pattern and ventilation during mental task performance. *Biological Psychology, 49*, 53–70.

Wierwille, W. W. (1979). Physiological measures of aircrew mental workload. *Human Factors, 21*, 575–593.

Wierwille, W. W. & Eggemeier, F. T. (1993). Recommendations for mental workload measurement in a test and evaluation environment. *Human Factors, 35*, 263–281.

Wiggins, J. S. (1973). *Personality and prediction: Principles of personality assessment*. Reading: Addison-Wesley.

Wilhelm, F. H., Gerlach, A. L., & Roth, W. T. (2001). Slow Recovery from voluntary hyperventilation in panic disorder. *Psychosomatic Medicine, 63*, 638–649.

Wilhelm, F. H. & Peyk, P. (2005). *ANSLAB: Autonomic nervous system laboratory (Version 4.0).* Society for Psychophysiological Research website. Retrieved from http://www.sprweb.org. Accessed September 3, 2012.

Wilson, G. F. (1993). Air-to-ground training missions: A psychophysiological workload analysis. *Ergonomics, 36*, 1071–1087.

Wilson, G. F. (2002). An analysis of mental workload in pilots during flight using multiple psychophysiological measures. *The International Journal of Aviation Psychology, 12*, 3–18.

Winkworth, A. L., Davis, P. J., Ellis, E., & Adams, R. D. (1994). Variability and consistency in speech breathing during reading lung volumes, speech intensity, and linguistic factors. *Journal of Speech, Language, and Hearing Research, 37*, 535–556.

Wright, R. A., Tunstall, A. M., Williams, B. J., Goodwin, J. S., & Harmon-Jones, E. (1995). Social evaluation and cardiovascular response: An active coping approach. *Journal of Personality and Social Psychology. 69*, 530–543.

Yasuma, F. & Hayano, J. I. (2004). Respiratory sinus arrhythmia: Why does the heartbeat synchronize with respiratory rhythm?. *Chest Journal, 125*, 683–690.

Yeh, Y. Y. & Wickens, C. D. (1988). Dissociation of performance and subjective measures of workload. *HumanFactors, 30*, 111–120.

Yerkes, R. M. & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology and Psychology, 18*, 459–482.

Young, M. S., Brookhuis, K. A., Wickens, C. D., & Hancock, P. A. (2014). State of science: Mental workload in ergonomics. *Ergonomics, 58*, 1–17.

Zaman, J., Van den Bergh, O., Fannes, S., & Van Diest, I. (2014). Learning to breathe: Feedforward regulation of the inspiratory motor drive. *Respiratory Physiology* & *Neurobiology, 201*, 1–6.

Zhang, J. (2007). Effect of age and sex on heart rate variability in healthy subjects. *Journal of Manipulative and Physiological Therapeutics, 30*, 374–379.

Zhu, Y., Hsieh, Y. H., Dhingra, R. R., Dick, T. E., Jacono, F. J., & Galán, R. F. (2013). Quantifying interactions between real oscillators with information theory and phase models: Application to cardiorespiratory coupling. *Physical Review E, 87*, 022709.

# Appendix

Table A. Overview of selected studies ($N = 54$) for reviewing respiration in response to mental task load.

| # | Authors | Year | *N* | Manipulation | | Outcome measures | Comments on methodology |
|---|---|---|---|---|---|---|---|
| | | | | Task type | Period analyzed (s) | | |
| 1 | Allen & Crowell | 1989 | 51 | ATT, MA | 180 | RR, TV, MV, $VO_2$, $VCO_2$ | |
| 2 | Althaus et al. | 1998 | 32 | MEM | 390 | RR | |
| 3 | Backs et al. | 2003 | 15 | MT | 30 | RR, TV | feedback |
| 4 | Backs et al. | 2000 | 27 | MT | 180 | RR | |
| 5 | Backs et al. | 1994 | 12 | PM | 180 | RR, TV | |
| 6 | Backs & Seljos | 1994 | 24 | MEM | 240 | RR, TV, $VO_2$, $VCO_2$ | verbal response, feedback |
| 7 | Barbosa et al. | 2010 | 17 | SI | n/a | RR | verbal response (one condition) |
| 8 | Beda et al. | 2007 | 25 | MA | 300 | RR (RP), TV, $T_i/T_e$ | verbal response (one condition) |
| 9 | Bernardi et al. | 2000 | 12 | MA | 180 | RR, MV | verbal response (one condition) |
| 10 | Brookings et al. | 1996 | 8 | MT | 300 | RR, TV | |
| 11 | Brouwer et al. | 2014 | 35 | MEM | 120 | RR (RP) | feedback |
| 12 | Burleson et al. | 1998 | 24[a] | MA | 360 | RR, TV | verbal response, feedback |
| 13 | de Visser et al. | 1995 | 43[a] | MEM | 600 | RR | feedback |
| 14 | Delistraty et al. | 1991 | 30 | MA | 60 | RR, TV, MV, $VO_2$, $VCO_2$, RER | |
| 15 | Dijksterhuis et al. | 2011 | 22 | MT | n/a | RR | |
| 16 | Duschek et al. | 2009 | 28 | ATT | 280 | RR | |

Table A. Continued.

| # | Authors | Year | *N* | Manipulation | | Outcome measures | Comments on methodology |
|---|---|---|---|---|---|---|---|
| | | | | Task type | Period analyzed (s) | | |
| 17 | Ettema & Zielhuis | 1971 | 24 | ATT | 60 | RR | |
| 18 | Fairclough et al. | 2005 | 30 | MT | 240 | RR | |
| 19 | Fournier et al. | 1999 | 10 | MT | 180 | RR, TV | |
| 20 | Grassmann et al. | in press | 61 | MT | 300 | RR, CV (RR), AR (RR), petCO$_2$ | |
| 21 | Herbert et al. | 2010 | 38 | MA | 300 | RR | feedback |
| 22 | Hoshikawa & Yamamoto | 1997 | 8 | SI | 630 | RR, TV, MV | feedback |
| 23 | Houtveen et al. | 2002 | 22 | MT | 240 | RR, petCO$_2$ | feedback |
| 24 | Karavidas et al. | 2010 | 7 | MT | 300 | RR, TV, MV | |
| 25 | Kodesh & Kizony | 2014 | 23 | RS | 30 | RR, TV, V$_e$, VO$_2$ | |
| 26 | Kuehl et al. | 2015 | 10[a] | ATT | 300 | RR | |
| 27 | Lackner et al. | 2010 | 20 | ATT, MA | 300 | RR | |
| 28 | Mehler et al. | 2009 | 111 | MT | 120 | RR | |
| 29 | Melis & van Boxtel | 2007 | 52 | RS | 270–584 | RR | |
| 30 | Niizeki & Saitoh | 2012 | 20 | MA | 180 | RR | feedback |
| 31 | Nilsen et al. | 2007 | 44 | CRT | 600 | RR | feedback |
| 32 | Novak et al. | 2012 | 24 | MA, PM, MT | 300 | RR, Var (RR) | verbal response, feedback |
| 33 | Overbeek et al. | 2014 | 83 | MEM | 150 | RR | |
| 34 | Papadelis et al. | 2007 | 10[a] | MT | 60 | RR | |

Table A. Continued.

| # | Authors | Year | *N* | Manipulation | | Outcome measures | Comments on methodology |
|---|---|---|---|---|---|---|---|
| | | | | Task type | Period analyzed (s) | | |
| 35 | Pattyn et al. | 2010 | 20 | SI | 120 | RR, TV, $T_i/T_{tot}$ | |
| 36 | | | 12[b] | SI | 120 | RR, TV, $T_i/T_{tot}$ | |
| 37 | Pattyn et al. | 2008 | 21 | VIG | 1800 | RR, TV | |
| 38 | Pruneti & Boem | 1995 | 23[a] | RS | n/a | RR | |
| 39 | Roman-Liu et al. | 2013 | 15 | ATT, VIG | 240 | RR | |
| 40 | Roy & Steptoe | 1991 | 10[a] | MA | 300 | RR | |
| 41 | Schleifer et al. | 2008 | 23 | MA, ATT | 360 | RR, $petCO_2$ | feedback (MA condition) |
| 42 | Silvia, Eddington, et al. | 2013 | 36 | CRT | 300 | RR | |
| 43 | Sloan et al. | 1991 | 10 | MA | 240 | RR | verbal response (one condition) |
| 44 | Sloan et al. | 1995 | 22 | MA, SI | 240 | RR | feedback |
| 45 | Steptoe et al. | 1997 | 132[a] | RS, PM | 300 | RR, TV | |
| 46 | Steptoe et al. | 1996 | 132[c] | RS, PM | 300 | RR, TV | |
| 47 | Troubat et al. | 2009 | 20 | RS | 300 | RR, TV, $VO_2$, $VCO_2$, RER | |
| 48 | Veltman | 2002 | 20 | MT | n/a | RR, TV | |
| 49 | Veltman & Gaillard | 1998 | 12 | MT | 240 | RR, TV, $T_i$ | feedback |
| 50 | Vlemincx et al. | 2011 | 43 | ATT, MA | 360 | RR, TV, MV, %RCi, SR, CV (RR), AR (RR), CV (TV), AR (TV), CV (MV), AR (MV) | feedback (MA condition) |

Table A. Continued.

| # | Authors | Year | *N* | Manipulation | | Outcome measures | Comments on methodology |
|---|---|---|---|---|---|---|---|
| | | | | Task type | Period analyzed (s) | | |
| 51 | Vlemincx et al. | 2012 | 47 | MA, ATT | 240 | RR, TV, MV, %RCi, SR, CV (RR), AR (RR), CV (TV), AR (TV), CV (MV), AR (MV) | feedback (MA condition) |
| 52 | Vögele & Steptoe | 1992 | 37 | MA, PM | 300 | RR | feedback |
| 53 | Wetzel et al. | 2006 | 80 | MA | 60 | RR, TV | verbal response, feedback |
| 54 | Wientjes et al. | 1998 | 44 | MEM | 300 | RR, TV, MV, $TV/T_i$, $T_i/T_{tot}$, $petCO_2$ | feedback (one condition) |

*Note*. [a] control group/condition, [b] sample of second experiment reported in Pattyn et al. (2010), [c] same sample as Steptoe et al. (1997), MA: mental arithmetic, SI: Stroop interference, MEM: memory, RS: reasoning, PM: psychomotor, MT: multiple task, CRT: choice reaction time, ATT: attentional, VIG: vigilance, RR: respiratory rate, RP: respiratory period (inverted direction of significant effects was used to integrate findings with RR), TV: tidal volume, MV: minute ventilation, $T_i$: inspiratory time, $T_i/T_e$: inspiratory/expiratory ratio, $TV/T_i$: mean inspiratory flow rate, $T_i/T_{tot}$: inspiratory duty cycle, $V_e$: expiratory volume, %RCi: contribution of ribcage breathing to inspiratory volume, SR :sigh rate, Var: variance, CV: coefficient of variation, AR: autocorrelation, $petCO_2$: partial pressure of end-tidal carbon dioxide, $VO_2$: oxygen consumption, $VCO_2$: carbon dioxide production, RER: respiratory exchange ratio.