Psychological and physiological responses to stress
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Psychological and physiological responses to stress

Jan H. Houtveen
Psychological and physiological responses to stress

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Physiological responses to mental stress are regulated by the sympathetic nervous system (SNS) including the sympathetic adrenal medullary (SAM) axis, the parasympathetic nervous system (PNS), and the hypothalamic pituitary adrenocortical (HPA) axis (e.g., see Johnson & Anderson, 1990; Lovallo & Thomas, 2000). The main function of these autonomous systems is to maintain internal homeostasis (Cannon, 1915). They regulate increased energy consumption during exercise and they also influence other physiological systems, such as immune function (Lovallo & Thomas, 2000). These systems react not only in response to exercise, but they also react in response to mental stress in order to adjust internal homeostatic processes in anticipation of a possible action in the near future (i.e., the fight-flight response).

Several non-invasive techniques exist to estimate SNS, SAM, PNS, and HPA reactivity to stress situations. Sympathetic nervous reactivity may be non-invasively estimated by changes in the galvanic skin response (Boucsein, 1992; Dawson, Schell, & Filion, 2000) or (regarding the beta-adrenergic drive to the heart) by changes in the pre-ejection period (PEP) derived from the impedance-cardiogram (Cacioppo, 1994; Sherwood et al., 1990). Reactivity of the SAM axis may be non-invasively estimated by changes in the level of urinary adrenaline and/or noradrenaline, although an estimation of changes in the level of plasma adrenaline appears to be more valid and reliable (Goldstein, 1995). Parasympathetic reactivity (regarding the vagal control of heart rate) may be non-invasively estimated by changes in respiratory sinus arrhythmia (RSA) derived from the electro-cardiogram (Berntson et al., 1997; Cacioppo, 1994). Finally, reactivity of the HPA axis may be non-invasively estimated by measuring cortisol in saliva using salivettes (Kirschbaum & Hellhammer, 1989).

The original research plan for this thesis was to test a speculative idea based on relatively old literature. According to this idea, individual differences in psychological defense mechanisms (i.e., cognitive avoidance of negative emotions) should be reflected in individual differences in response patterns of the SAM, PNS, and HPA axes to mental stress. However, during an initial review of recent literature undertaken to sharpen the experimental design (chapter 2), severe methodological and theoretical issues surfaced regarding the joint reactivity of the SAM and HPA axes. Only very recently, Sapolsky and co-workers (2000) have provided guidelines on how to deal with these problems. As a consequence, this thesis has additionally focused on responses of the ‘third axis’ (i.e., the PNS
Chapter 1

branch of the autonomous nervous system) and on central physiological responses to mental stress. Thus, although the main research question of this thesis remained whether individual differences in cognitive avoidance of negative emotions are reflected in individual differences in physiological responses to mental stress, sympathetic, cardiac vagal, and central EEG responses were measured instead of reactivity of the SAM and HPA axes.

This thesis consists of two main parts. Part I (chapters 2 to 4) deals with theoretical and methodological issues that are of relevance for the assessment of physiological responses to mental stress. Chapter 2 reviews the literature in favor of a dualism in the reactivity of the SAM and HPA axes to mental stress. This dualistic view assumes that specific psychological characteristics of a stress situation lead to differential patterns of reactivity of the SAM and HPA axes. Concisely, it has been suggested that effort induces increased SAM activation, whereas (perceived) distress triggers increased HPA activation (e.g., see Lovatto & Thomas, 2000; Lundberg & Frankenhauser, 1980). This situational specificity is tacitly assumed to reflect a broader (dispositional) difference in the preferred emotional coping style (see Henry & Stephens, 1977). Evidence for both situational and dispositional specificity in the reactivity of the SAM and HPA axes is examined in chapter 2.

Chapters 3 and 4 tackle the two main issues regarding the estimation of PNS regulation of heart rate (i.e., cardiac vagal tone) by means of RSA. Chapter 3 deals with the question of whether frequency domain or time-frequency domain measures should be used to estimate RSA. This chapter examines the error made by violating the assumption of stationarity when using discrete Fourier transformation for spectral decomposition of heart period data. Chapter 4 deals with the complex relationship between cardiac vagal tone and RSA. This chapter examines whether and how RSA is co-determined (apart from the influence of cardiac vagal tone) by the central respiratory drive, tidal volume, and respiratory rate.

Part II of this thesis (chapters 5 to 7) deals with the relationship between individual differences in cognitive avoidance of negative emotions and individual differences in physiological responses to mental stress. Dispositions like a repressive emotional coping style or alexithymia have been suggested to increase autonomous physiological reactivity to mental stress (e.g., see Brown et al., 1996; Scheier & Bridges, 1995; Schwartz, 1990; Sifneos, 1973; Weinberger, Schwartz, & Davidson, 1979). It has, for example, been suggested that individuals with a repressive emotional coping style are characterized by relatively low self-reported negative affect despite having relatively high autonomous physiological responses (Schwartz, 1990; Weinberger, Schwartz, & Davidson, 1979). This combination may ultimately lead to an increase in physical disease (Scheier & Bridges, 1995; Schwartz, 1990; Ursin & Olff, 1993). The study described in chapter 5 was
designed to demonstrate increased stress-related autonomous physiological reactivity in individuals with a repressive emotional coping style, and to explore a relationship between a repressive emotional coping style and reduced habituation of autonomous physiological responses after repeated emotional stimulation.

However, a ‘mirror’ group of individuals may also be defined. These individuals suffer from functional somatic symptoms or somatization disorder (i.e., a medical explanation cannot be found; see Wesseley, Nimnuan, & Sharpe, 1999; Ursin, 1997). A relationship between functional somatic symptoms and the psychological trait negative affectivity (which is related to trait anxiety) has frequently been demonstrated (see Watson & Pennebaker, 1989; Wientjes & Grossman, 1994). Thus, in contrast to individuals characterized by a repressive emotional coping style, individuals belonging to this mirror group overtly demonstrate their negative affect, both verbally and with somatization. Chapter 6 describes a study on the autonomous physiological reactivity to mental stress in a group of individuals with numerous functional somatic symptoms.

The studies described in chapters 5 and 6 were designed to examine whether individual differences in cognitive avoidance of (stress-related) negative emotions are reflected in individual differences in (peripheral) autonomous physiological responses to mental stress. However, individual differences in cognitive avoidance of (stress-related) negative emotions may also be reflected in physiological differences at the level of the central nervous system. The final study described in chapter 7 compares alexithymic individuals and controls in a central physiological (i.e., EEG-coherence) response to mental stress.

The general discussion (chapter 8) summarizes the review and the results of the 5 studies of this thesis, attempts a synthesis of the main results, and makes methodological recommendations for further research.

References


Chapter I


Part I

Methodological and theoretical issues in studying physiological responses to stress
Human SAM and HPA responses to stress: a dualistic or an integrated system?

Jan H. Houtveen, Paul J. Lucassen, Jos F. Brosschot, & Eco J.C. de Geus

Abstract

The joined responses of the sympathetic adrenal medullary (SAM) axis and the hypothalamic pituitary adreno-cortical (HPA) axis are involved in mediating the effects of psychological stress on health. A popular view of SAM and HPA axes reactivity in response to stressful situations involves a strict dualism in reactivity of these two axes. This view implies that different psychological factors may differentially engage either the SAM or HPA axis. Mental effort has been described as inducing a rapid increase of catecholamine levels mediated through the SAM axis, while perceived distress has been described as triggering additional cortisol responses mediated through the HPA axis. Methodological problems in the studies that support this dualistic view are discussed. Finally, an alternative model is presented that explains the observed SAM and HPA response patterns by variations in the intensity of psychological stress, concurrent muscular activation, and the occupation of glucocorticoid receptors for cortisol. This model may help to better understand the (often paradoxical) effects of hormonal responses to different types of psychological stress as reported in the literature, without introducing a dualism in an obviously integrated physiological response system.
Introduction: the SAM and HPA axes

The physiological response to psychological stress situations encompasses both the sympathetic adrenal medullary (SAM) axis and the hypothalamus pituitary adreno-cortical (HPA) axis (e.g., Cacioppo, 1994; Dienstbier, 1989; Johnson, Kamilaris, Chrousos, & Gold, 1992; Lovallo & Thomas, 2000; Mason, 1968a; Mason, 1968b; Sapolsky, Romero, & Munck, 2000; Stratakis & Chrousos, 1995). These stress-related responses of the SAM and HPA axes are considered important mediators for the effects of psychological stress on health. A popular view states that different psychological factors may preferentially engage either the SAM or HPA axis (e.g., see Lovallo & Thomas, 2000). The current paper evaluates the evidence for this 'dualistic' model of SAM and HPA reactivity in response to different types of stressful situations. An alternative model will be presented that explains the observed SAM and HPA response patterns by variations in the intensity of psychological stress, concurrent muscular activation, and the occupation of the glucocorticoid receptors for cortisol in the brain. This occupation is influenced by circadian rhythms as well as the ongoing level of stress (i.e., the duration of the stressor).

The sympathetic nervous system, as part of the autonomic nervous system, prepares the individual organism for a fast fight or flight response after exposure to a stressor (Cannon, 1915). Following a specific appraisal phase (occurring within seconds) when an organism judges whether the situation is actually threatening, the behavioral response focuses on defensive behavior or, when a challenging other is dominant, flight. Physiologically, this fast response includes all main sympathetic targets (i.e., cardiac, splanchnic, renal, muscle-vascular systems, etc.). The sympathetic nervous system coordinates these responses through release of adrenaline (and to a lesser degree noradrenaline) into the blood by the SAM axis. As a consequence there is a selective increase in blood flow in muscular tissue, an increase in the noradrenergic drive to cardiac muscle and blood vessels, an increase in cardiac output and blood pressure, and an increase in the release of glucose from the liver (Mason, 1968b). The SAM response generates a fast and non-specific state of alarm to meet the special requirements of an emergency situation (Mason, 1968b). In the first phase this response tends to overshoot the actual physiological demand, but in a later stage sympathetic activation is tuned to a level that is just sufficient to maintain homeostasis.

When the intensity and duration of stress are sufficient, an increase is also elicited in the activity of the HPA axis (De La Torre, 1994; Lovallo & Thomas, 2000; Mason, 1968a; Sapolsky et al., 2000; Selye, 1936). HPA activation starts at corticotrophin-releasing factor (CRF) producing neurons in the paraventricular nucleus (PVN) of the hypothalamus. These neurons mainly project to several areas of the brainstem, including the sympathetic control areas, but CRF is also released within seconds after encountering a stressor, acting as a neuropeptide that stimulates adreno-corticotropin hormone (ACTH) release from the anterior
pituitary into the blood (Stratakis & Chrousos, 1995; Kvetnanski et al., 1995; Pacák et al., 1995; Sapolsky et al., 2000). ACTH, in its turn, stimulates the adrenal cortex to release glucocorticoids (cortisol). The central CRF system has a major function in regulating behavioral, autonomic (sympathetic and SAM), and HPA responses to stress (Stratakis & Chrousos, 1995; Kvetnanski et al., 1995; Pacák et al., 1995; Sapolsky et al., 2000). It is controlled and kept within physiological limits by negative feedback that is mediated through cortisol receptors that are present throughout the brain, but concentrated in high densities in the hippocampus, pituitary, and hypothalamus. Together they regulate the amount of CRF released by the PVN. As a result of this complex regulatory system, responsiveness of the HPA axis is considerably slower than responsiveness of the SAM system. Although some relatively fast effects of steroid hormones have been reported by means of rapid second messenger cascade mechanisms (Wehling, 1997), the bulk of the cortisol effects are genomic and do not occur until about several hours after the onset of a stressor (Sapolsky et al., 2000).

Cortisol (in primates) mobilizes energy and enhances metabolism. It stimulates the conversion of fats and proteins into glucose, and it is associated with an increased number of circulating free fatty acids (De La Torre, 1994; Johnson et al., 1992; Munck, Guyre, & Holbrook, 1984). Secondly, cortisol facilitates essential processes by suppressing several less acute, anabolic activities (such as growth, repair, reproduction, digestion, and inflammation) that may be important in the long run, but are not essential for survival under the given emergency conditions (De La Torre, 1994; Munck et al., 1984; Johnson et al., 1992). Thirdly, cortisol may have an enhancing and/or activating (permissive) function in the stress response (e.g., cortisol may increase blood pressure and cardiac output; see Sapolsky et al., 2000). Finally, cortisol may have a protective (suppressive) function. For example, it may protect against excessive or toxic damage exerted by catecholamines released by the sympathetic nervous system (Kapcala, Chautard, & Eskay, 1995; Munck et al., 1984; Sapolsky et al., 2000). The metabolic function of cortisol may have its effects during the initiation phase as well as during continuation of an alarm situation, whereas the slower (genomic) activating and protective functions of cortisol (permissive or suppressive) may have its effects solely during prolonged continuation of an alarm situation. It has been suggested that the permissive and suppressive effects of cortisol complement each other, the former preparing or priming defense mechanisms for action, and the latter limiting the actions of those primary defenses (i.e., to prevent them from overshooting) and to bring about recovery (Munck et al., 1984).

Glucocorticoids (cortisol) are highly lipophilic molecules that easily pass the blood-brain barrier, where they bind to two types of specific receptors in the major HPA feedback-regulation areas located in the brain: the glucocorticoid receptor (GR) and the mineralocorticoid receptor (MR; DeKloet, Vreugdenhil, Oitzl, & Joels, 1998). Together, both GR and MR receptors control feedback regulation of HPA activity. However, the MR has a tenfold higher affinity for cortisol than the
GR. Consequently, the MR is almost always occupied whereas the GR becomes occupied only during the circadian peak (about 1.5 hours after awakening) or during prolonged stress (De Kloet et al., 1998). The MR is thought to be involved in maintaining basal activity (proactive mode) of the HPA axis, whereas the GR is involved in reactivity (reactive mode) to maintain homeostasis (De Kloet et al., 1998). Most permissive actions of cortisol may be exerted through MR occupation, while suppressive actions may be exerted mainly through GR occupation (Sapolsky et al., 2000).

The SAM and HPA axes may be easily described as separate systems, each with a differential time-scale for the appearance of its major hormones (i.e., adrenaline and cortisol). However, the major point to be made in this paper is that, during stress, they will function as strongly integrated systems. The feedback control areas of the HPA axis (i.e., that regulate the release of cortisol by central GR and MR occupation) are also involved in the release of plasma catecholamines by the SAM axis (Kvetnansky et al., 1995; Munch et al., 1984). These effects of cortisol on the reactivity of the SAM axis may be permissive or, under specific conditions with high GR occupation, suppressive (Sapolsky et al., 2000). Thus, the reactivity of both the SAM and HPA axes is influenced by CRF neurons in the PVN and both systems may be down-regulated through GR occupation. Furthermore, many other reciprocal anatomical connections between the SAM and the HPA control regions have been demonstrated (Stratakis & Chrousos, 1995; Kvetnanski et al., 1995; Pacák et al., 1995).

Peripherally, SAM and HPA regulation also interact. In the adrenal medulla, adrenaline and noradrenaline are secreted by chromaffin cells (McGeer & McGeer, 1980). Haidan and co-workers (1998) demonstrated (in vitro) that chromaffin cells are involved in the release of cortisol as well. Moreover, chromaffin cells are characterized by the presence of phenylethanolamine-N-methyl-transferase (PNMT), which converts noradrenaline into adrenaline. Cortisol is released from the adrenal cortex and delivered preferentially to the medulla via the adrenal portal vascular system, where it induces the synthesis of PNMT in chromaffin cells. Thus, the extent to which adrenaline may be secreted is likely to depend on the amounts of cortisol released. Cortisol may also modify adreno-receptor sensitivity (Kvetnanski et al., 1995). In short, activity of the SAM and HPA axes, and the ensuing release of adrenaline and cortisol, is strongly coupled in the central nervous system as well as in the adrenal medulla and cortex. This coupling is not surprising since the SAM and HPA axes have mutually

1. The results of Kvetnansky and co-workers (1995) demonstrated that the suppressive effects of cortisol on the production of catecholamines reversed when cortisol was continuously administered for 7 days. These results illustrate the fact that the regulating effects of cortisol may be totally different during periods of chronic cortisol elevation (i.e., are truly context dependent).
supportive roles in their homeostatic functions (e.g., in glucose-metabolism; Stratakis & Crousos, 1995).

**Two separate systems?**

In spite of the above, the SAM and HPA axes are traditionally considered as two separate and independently regulated systems. This separation is derived from the classical model of Henry and Stephens (1977), mainly based on animal studies, in which SAM reactivity is thought to occur mainly under fight or flight, active effortful coping conditions (Cannon, 1915; Henry, 1986; Henry, Stephens, & Elly, 1986; Mason, 1968b), whereas reactivity of the HPA axis is thought to be evoked mainly in loss of control, passive conservation-withdrawal conditions (Engel & Schmale, 1972; Henry, 1986; Henry et al., 1986; Mason, 1968a). Thus, the SAM and HPA axes appear to respond differentially when animals are subjected to different situations. Apart from this situational specificity, evidence was found for a dispositional preference for SAM versus HPA reactivity, strongly coupled to the preferred coping style of an animal. Within any group of animals, two extreme ends of the distribution of coping strategies may be discriminated that differ with respect to behavioral, physiological, and central nervous system activities (e.g., see Benus, Bohus, Koolhaas, & van Oortmerssen, 1989). Such within-species differences in coping responses have been related to differences in SAM and HPA responses (e.g., see Fokkema, Smit, VanderGugten, & Koolhaas, 1988).

An example of within-species differences in coping responses is the difference between the short attack latency (SAL) and long attack latency (LAL) mice. These mice are genetically homogeneous but have been inbred for several generations to amplify the individual extremes of aggression and stress responses (Benus, Bohus, Koolhaas, & van Oortmerssen, 1991; Oortmerssen & Busser 1989; Koolhaas et al., 1999). SAL mice show increased aggressive behavior when an intruder is placed in the home cage, whereas LAL mice wait much longer before attacking. These groups may, to some extent, be considered representative for animals or individuals that will predominantly show a fight or flight response versus individuals displaying a preference for the conversation-withdrawal responses respectively (Engel & Schmale 1972). These differences in coping responses are paralleled by a high sympathetic reactivity of the SAL mice, and a preferentially parasympathetic response combined with a strongly enhanced cortisol responses to CRF in the more passive LAL mice (Fokkema et al., 1988). Similar within-species differences in physiological reactivity to stressors were also found between two Wistar rat lines selectively bred for high-anxiety-related behavior (HAB) and low-anxiety-related behavior (LAB; see Liebsch et al., 1998).

Thus, in these strongly inbred animals, many of the predictions on how specific types of animals react to specific stress situations, as described by Henry and Stephens (1977), have been tested and confirmed. Does a dualistic view on
SAM and HPA reactivity also hold for human subjects? The results of a number of situational specificity studies suggest that SAM axis reactivity appears to be triggered predominantly by mental load, effort, or activation (Lovallo, Pincomb, & Wilson, 1986b; Lundberg & Frankenhausser, 1980; Obrist et al., 1978; Peters et al., 1998), while HPA axis reactivity is triggered by perceived novelty (Brandenberger, Follenius, Wittersheim, & Salame, 1980; Wittersheim, Brandenberger, & Follenius, 1985; Davis, Gass, & Bassett, 1981), perceived lack of controllability (Bohlin, Eliasson, Hjemdahl, Klein, & Frankenhausser, 1986; Breier, et al., 1987; Netter, Croes, Merz, & Müller, 1991), or perceived distress (Lovallo, Pincomb, & Wilson, 1986a; Lundberg & Frankenhausser, 1980; Peters et al., 1998). Humans also seem to show evidence of a behavioral disposition that makes either SAM or HPA axis activation the dominant response to most stressors. Specifically, human individual differences in SAM axis hyper-reactivity are ascribed to the cardiovascular ‘disease-prone’ personality (e.g., type A, competitiveness, and hostility; Suls & Wan, 1993), whereas HPA axis hyper-reactivity is ascribed to a disposition for depression and depressive coping (Nemeroff et al., 1984; Gold, Goodwin, & Chrousos, 1988). At first glance, prospective studies on the effects of chronic psychosocial stress on health seem to support this dualism. Subjects with a disposition towards chronic active coping (e.g., related to work stress) and high levels of hostility have a higher risk for cardiovascular disease (Lynch, Krause, Kaplan, Tuomilehto, & Salonen, 1997; Siegman & Smith, 1994), in which sympathetic hyperreactivity is considered to be a major etiological agent. Impaired immune function, in which HPA dysfunction may play a major role, has been found mainly in conditions of chronic passive coping (bereavement, care-taking of ill partner, AIDS) and in subjects with a disposition towards depression (Glaser & Kiecolt-Glaser, 1994). However, it is becoming increasingly clear that immune function is also influenced by SAM activity (e.g., see Schedlowski, Hosch, Oberbeck, & Schmidt, 1994) and that a risk for cardiovascular disease is also influenced by HPA activity (e.g., see Fraser et al., 1999).

Some crucial studies will be discussed in more detail below to test the robustness of the evidence for a situational and dispositional dualism of the reactivity of the SAM and HPA axes in humans. In their classic paper, Lundberg & Frankenhausser (1980) found independent psychological sources of variance for SAM and HPA activation in the effort versus distress dimensions. They designed five different experimental situations (tasks) to induce different degrees of mental effort coupled with either distress or positive affect. After the experimental task (70 minutes) urinary cortisol and catecholamines were measured. A monotonous vigilance task (experienced as both distressing and effort-demanding) resulted in an increase in both cortisol and adrenaline, but not in noradrenaline. However, a self-paced reaction time task (experienced as effort-demanding but not as distressing) produced an increase in both adrenaline and noradrenaline, but a
decrease in cortisol. The authors concluded that effort activates the release of catecholamines, while additional distress was essential for cortisol release.

Two methodological problems may have flawed these conclusions. First, urinary adrenaline may not reliably indicate activity of the SAM axis (Ziegler, Aung, & Kennedy, 1997). Secondly, the different tasks had been performed at different times, which may be considered a confounding factor. Relatively high GR occupation exists during the early morning hours as compared to later hours (De Kloet et al., 1998). The monotonous vigilance task had always been performed relatively short after the early morning circadian peak which thus induced (additionally to MR) relatively high GR occupation (i.e., 8:30 - 9:40 AM), while the self-paced reaction time task had always been performed a few hours later during a situation with much less GR occupation (i.e., 10:50-12:00 AM). Because suppressive actions of cortisol are exerted mainly by GR occupation (Sapolsky et al., 2000), different experimental times may have resulted in differences in permissive versus suppressive actions of this regulatory system. These actions also involve the release of plasma catecholamines by the SAM axis (Munck et al., 1984; Kvetnansky et al., 1995). Thus, the adrenaline response to the early monotonous vigilance task may have been more suppressed than the adrenaline response to the self-paced reaction time task. Additionally, only the monotonous vigilance task may have produced enough (di)stress to result in a cortisol response. Thus, rather than specific task characteristics, the differences in the level of (di)stress combined with differences in (initial) GR occupation as a result of different experimental times may have explained the differential catecholamine and cortisol responses of this study.

Frankenhauser, Lundberg, and Forsman (1980) compared Type A and Type B men and women on a choice-reaction task. They measured urinary adrenaline, noradrenaline, and cortisol at the end of the task. Their results demonstrated an overall increase in the secretion of catecholamines and a decrease in cortisol. The increase in catecholamines was interpreted in terms of the mobilization of effort induced by the task. The decrease in cortisol was interpreted in terms of the high level of personal control (low distress) while performing the task. However, the time of measurement (i.e., 10:50-12:00 AM) was identical to that of the effort demanding/low distress task of the previous experiment (see above). The decrease in cortisol probably resulted from the well-known morning decrease due to the circadian rhythm. Also, a low (initial) GR occupation may very well have been responsible for the relative high catecholamine levels during this low stress task. Although comparison of physiological measures between sexes may be problematic, closer observation of the differences between men and women suggests that the amount of released adrenaline was actually correlated to the amount of released cortisol. Men, as compared to women, reported more effort, secreted more adrenaline, and they had less decrease of cortisol.

Peters and co-workers (1998) used a factorial design in which mental effort was manipulated by a high effort mental arithmetic task versus a low effort key-
press task, while control (and success on the task) was independently manipulated by the amount of controllability and predictability regarding the noise intensity presented to them during the task. They found a main effect of both effort and control on noradrenaline, and only a main (and relatively small) effect of control on cortisol. No meaningful effects were found for adrenaline. Their data would have been more illustrative of a dualistic SAM and HPA reactivity when a main effect of effort was found on adrenaline (high effort should always produce more SAM activation), combined with an effort by control interaction effect on cortisol (increased HPA activation should only be found when high effort is combined with low control). However, such effects were not found.

Lovallo and Thomas (2000) referred to two other studies that (when combined) might suggest differential effects of effort versus distress on SAM and HPA activation. In the first study, a significant rise in both noradrenaline and cortisol secretion was found after 15 minutes of a reaction time task in which subjects had to perform well to avoid noise bursts and electric shocks (Lovallo, Pincomb, & Wilson, 1986a). In the second study, only a significant rise in noradrenaline (no change in cortisol) was found after subjects had performed a nearly identical reaction time task for monetary reward (Lovallo, Pincomb, & Wilson, 1986b). Self-reports showed increases in both effort and distress during the noise bursts and shock avoidance task, but only increases in effort during the monetary reward task. Lovallo and Thomas (2000) concluded that cortisol is preferentially responsive to the subjective states of distress, while catecholamines are responsive to states of ‘activation’, regardless of the emotional valence. However, between-task differences in heart rate and blood pressure responses indicate that the first described task (i.e., the cortisol producing task) may have resulted in an overall higher autonomic activation as compared to the second. The intensity of the stressor may have been sufficient for cortisol release for the first study, but it may not have been sufficient for the second study.

Another main complication in accepting the conclusions of both Peters and co-workers (1998) and Lovallo and Thomas (2000) is that they hinge in part on a differential noradrenaline response. However, noradrenaline levels may not always reliably indicate SAM axis activation. High plasma noradrenaline levels during effortful tasks may also be explained by increased muscle tension. Muscle tension results in reflexogenic local plasma release of noradrenaline from the sympathetic nerve endings that innervate the muscle vasculature (e.g., see Goldstein, 1995). Increases in muscle tension may be more apparent during states of anger and/or defense as compared to states of fear and defeat (Ax, 1953; Henry, Stephens, & Ely, 1986). Thus, noradrenaline responses may falsely suggest a differential psychological effect on SAM reactivity if the tasks used to induce effort versus distress differ in the evoked muscular tension. Goldstein (1995), who reviewed plasma noradrenaline responses, more broadly concluded that this particular measure does not give a valid indication of sympathetic nervous system
activity. Only plasma adrenaline reactivity may be a reliable indicator of SAM axis reactivity to psychological stress.

The studies described above have often been quoted to illustrate that mental effort influences activity of the SAM axis, while perceived psychological distress (as a result of perceived novelty, unpredictability, or lack of control) influences activity of the HPA axis. Although attractive at face value, a strict situational dualism in the reactivity of the SAM and HPA axes in humans did not hold up in our evaluation of the current evidence. The few studies that have tested dispositional differences in the reactivity of the SAM and HPA axes in humans actually contradict a dualism. Cacioppo (1994) demonstrated a significant positive correlation between stress-induced increases in cardiac sympathetic drive and stress-induced changes in plasma cortisol concentrations. Likewise, al’Absi and co-workers (1997) showed a significant correlation between sympathetic reactivity and HPA axis reactivity. They additionally provided evidence that this correlation becomes apparent only during intensive stressors, like public speaking. Finally, Kirschbaum and co-workers (1996) showed that a short term elevation of estradiol levels not only exaggerates the ACTH and cortisol responses to psychosocial stressors, but it also exaggerates noradrenaline and heart rate responses.

An alternative model

What has been demonstrated convincingly so far is that increases in plasma adrenaline may occur independently of increases in plasma cortisol, and that neither increases in plasma adrenaline nor cortisol need to occur in parallel to increases in plasma noradrenaline. But do the various possible combinations of reactivity of plasma adrenaline, noradrenaline, and cortisol reflect distinct psychological dimensions of the stressors that evoke them? We will attempt a more parsimonious model that avoids psychological multidimensionality. We propose that variations in the intensity of psychological stressors of all types (e.g., competition with effort, uncontrollability with distress), the amount of muscle tension, and the ongoing central MR and GR occupation may result in several distinct catecholamine-cortisol responses.

Intensity of the stressors is important because activation of the HPA axis is slower and has a higher threshold level (in intensity and/or duration of stress) than activation of the SAM axis (e.g., De La Torre, 1994; Lovallo & Thomas, 2000; Mason, 1968a; Selye, 1936). Results described in Lovallo and Thomas (2000) and the study of al’Absi and co-workers (1997) seem to support the importance of the intensity of the stressor as a determinant of SAM and HPA patterning.

The amount of muscle tension caused by a stressor is important because the levels of plasma noradrenaline may largely depend upon it. A distinction should be
made between an activation dimension (defined here as an increase in action
tendency and related muscle tension), and a psychological stress dimension. A
high level of activation results in a relatively strong increase in plasma
noradrenalin (resulting from increased muscle tension), while a high level of
psychological stress results in a relatively strong increase in plasma adrenaline
(resulting from activation of the SAM system).

Finally, the ongoing central GR occupation is important, since this may
influence the balance in the release of plasma cortisol and adrenaline. Suppressive
actions of cortisol are exerted mainly by GR occupation (Sapolsky et al., 2000).
These suppressive actions also involve the release of plasma catecholamines by
the SAM axis (Munck et al., 1984; Kvetnansky et al., 1995). Thus, regardless of
persistent MR occupation, the feedback control loop of the HPA axis is also able to
either facilitate (by selective MR occupation) or suppress (by additional GR
occupation) the release of adrenaline by the SAM axis. The initial GR occupation,
therefore, critically determines the pattern of adrenaline and cortisol responses to
stress. Because GR occupation is related to initial cortisol levels, the circadian
rhythm is an important determinant of GR occupation (De Kloet et al., 1998). GR
occupation is further determined by the duration of the current stressor, or by a
history of (chronic) stress (De Kloet et al., 1998).

After a low stress period with low initial GR occupation (i.e., the initial
cortisol level was low), relatively moderate levels of plasma adrenaline combined
with relatively low levels of cortisol may be found because no suppressive actions
are exerted. After a high stress period with initially high GR occupation (i.e., the
initial cortisol level was high), relatively moderate levels of plasma adrenaline
combined with relatively high levels of cortisol may be found because suppressive
actions are exerted. The lowest levels of adrenaline and cortisol may be found after
initially high GR occupation combined with low stress, and the highest levels may
be found after initially low GR occupation combined with high stress. Finally,
muscle tension related to activation may independently contribute to the
noradrenaline levels.

An illustration of different predicted catecholamine and cortisol reactivity
patterns, as a result of differences in the level of intensity for activation and
psychological stress and differences in the GR occupation at the initiation of a
stressor, is shown in Table 1. Although the units in this Table are completely
arbitrary, the relations between activation levels and suppression rates are
illustrative of our alternative model. The mathematical rules used are: (a) the level
of released adrenaline by the SAM axis is always four times the level of
noradrenaline (i.e., peripheral interactions are ignored); (b) a high intensity
stressor, as compared to a low intensity stressor, results in a two-fold increase of
SAM responses and an eight-fold increase of HPA responses (based on a higher
threshold for stress-related activation of the HPA axis); and (c) an initially high
GR occupation results in halving both the SAM and HPA responses. Table 1
illustrates that the catecholamine-cortisol balance may vary without the need for a
distinct psychological source of SAM and HPA axis activation. At the same time, it is fairly easy to project all the findings of previous human studies on this table. For instance, the selective noradrenaline response to reaction time task performance for monetary bonuses (Lovallo et al., 1986b; described in Lovallo and Thomas, 2000) could reflect the two ‘high intensity’ cells of the ‘activation no stress’ column. Additionally, the joint cortisol and noradrenaline responses to the reaction time task to avoid presentation of noise bursts and electric shocks (Lovallo et al., 1986a; described in Lovallo and Thomas, 2000) could reflect the high intensity cells of the ‘activation and stress’ column.

Table 1. Predicted time integrated release (in arbitrary units 1-16) of plasma adrenaline (A), plasma noradrenaline (NA), and cortisol (cort) for two levels of GR receptor occupation at the initiation of the stressor, and two levels of intensity for activation and/or psychological stress.

<table>
<thead>
<tr>
<th>MR/GR occupation</th>
<th>intensity</th>
<th>activation</th>
<th>stress</th>
<th>activation and stress</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>stressor</td>
<td>(no stress)</td>
<td>(no activation)</td>
<td></td>
</tr>
<tr>
<td>MR/lowGR’</td>
<td>low</td>
<td>+4NA</td>
<td>+2NA</td>
<td>+6NA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
<td>+8A</td>
<td>+8A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
<td>+2cort</td>
<td>+2cort</td>
</tr>
<tr>
<td>MR/lowGR’</td>
<td>high</td>
<td>+8NA</td>
<td>+4NA</td>
<td>+12NA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
<td>+16A</td>
<td>+16A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
<td>+16cort</td>
<td>+16cort</td>
</tr>
<tr>
<td>MR/highGR”</td>
<td>low</td>
<td>+4NA</td>
<td>+1NA</td>
<td>+5NA</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
<td>+4A</td>
<td>+4A</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
<td>+1cort</td>
<td>+1cort</td>
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<td>+2NA</td>
<td>+10NA</td>
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<td>+8A</td>
<td>+8A</td>
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<tr>
<td></td>
<td></td>
<td>-</td>
<td>+8cort</td>
<td>+8cort</td>
</tr>
</tbody>
</table>

Notes: ‘Relatively high levels of released catecholamines from the SAM axis may be found as a result of the permissive function exerted through (only) MR occupation. ‘Relatively low levels of released catecholamines from the SAM axis may be found as a result of the suppressive function exerted through (additional) GR occupation, that may have resulted from previous stress or the circadian rhythm.

Thus, variations in the intensity of psychological stressors combined with variations in the amount of muscle tension and variations in the ongoing central GR occupation may be sufficient to account for all complex (but coordinated) reactivity patterns of the human SAM and HPA axes described in the literature. This alternative model is based on mutual central (and peripheral) interactions.
between the SAM and HPA axes. Plasma adrenaline levels (not noradrenaline) reliably indicate SAM axis reactivity and are predicted to correlate with cortisol. Thus, reactivity in both plasma adrenaline and cortisol may indicate a high level of psychological stress.

Recently, the accent has shifted from stress-reactivity studies to a more dynamic view in which the total pattern of reactivity and recovery is observed during psychological stress situations (Linden, Earle, Gerin, & Christenfeld, 1997). This shift is based on new insights showing that in addition to (or even more importantly than) high reactivity, slow recovery or an aberrantly set hormonal balance, might influence the development of a disease process (Dienstbier, 1989; Linden et al., 1997).

A shift in focus towards the temporal patterns of reactivity and recovery of the physiological axes that respond to stress situations, and their inter-relationships, requires abandoning the strict separation of these axes as is now (often implicitly) adopted in the literature. The model presented here may be considered a physiological model of slow recovery, which might influence the development of a disease process or even brain pathology and affective disorders. It would be of great interest to observe individual differences in the reactivity of the SAM and HPA axes in response to moderate and intense stress situations, and under different conditions of (initial) GR occupation as a result of circadian rhythms, previous stressors, or medication. Such an approach is likely to be of great value in the study of specific stress-related disorders and on the effects of stress on health and well being in general.

References


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Human SAM and HPA responses to stress


Human SAM and HPA responses to stress


Chapter 2


Comparison between the Fourier and Wavelet methods of spectral analysis applied to stationary and non-stationary heart period data

Jan H. Houtveen & Peter C.M. Molenaar

Abstract

The aim of this study was to assess the error made by violating the assumption of stationarity when using Fourier analysis for spectral decomposition of heart period (HP) power. A comparison was made between using Fourier and Wavelet analysis (the later being a relatively new method without the assumption of stationarity). Both methods were compared separately for stationary and non-stationary segments. An ambulatory device was used to measure the HP data of 40 young and healthy participants during a psychological stress task and during periods of rest. Surprisingly small differences (< 1%) were found between the results of both methods, with differences being slightly larger for the non-stationary segments. It is concluded that both methods perform almost identically for computation of HP power values. Thus, the Wavelet method is only superior for analysing HP data when additional analyses in the time-frequency domain are required.
Introduction

Heart rate (or heart period) variability has been found to be useful to assess autonomic nervous system activity. Results using spectral analysis of heart period variability have demonstrated that heart period variability power can be divided into three major frequency bands, which provide separate information concerning the sympathetic and parasympathetic nervous systems (see Berntson et al., 1997). The high frequency (HF) power (i.e., the respiratory frequency band) is considered to range (nominally) from about 0.15 Hz to 0.4 Hz. The integrated power within this high frequency band is generally believed to be an index of cardiac vagal control. The low frequency (LF) band generally ranges from 0.05 Hz to 0.15 Hz. The integrated power within this low frequency band is believed to reflect both sympathetic and vagal control of heart rate. Frequencies below 0.05 Hz are sometimes identified as very low and/or ultra low frequency (VLF, ULF) bands. Some researchers also use the LF/HF power ratio as an index of the cardiac sympatho-vagal balance.

Recently, Berntson and co-workers (1997) published an extensive review article in which the origins, methods, and interpretative caveats of heart period variability measures were discussed in great detail. In summary, these authors concluded that patterns of heart period variability have proved useful in psychophysiological applications in the past and hold considerable promise as psychophysiological measures in the future, but that there are methodological and interpretative pitfalls. One of the methodological pitfalls mentioned by Berntson and co-workers, that is of particular relevance here, is the assumption of stationarity. Stationarity of time series may be interpreted as having at least a stable mean and variance over time. Most widely used spectral analysis methods of heart period variability (like Fourier transformation) assume that the data show at least weak stationarity (i.e., have a stable mean and variance). However, it is difficult to find a clear estimate in the literature of the size of the error made as a result of violating this assumption. Especially in the fields of physiology of emotion and ambulatory measurements of heart period data, the assumption of stationarity might be strongly violated. The aim of this study is to assess the differences between Fourier transformation (a widely used stationarity-assumption based method) and spectral analysis by the Wavelet method (a relatively new method that is not based on the assumption of stationarity) applied to the same interbeat interval (IBI) data set.

Heart period (uniformly spaced) time series may be transformed into a spectral density function by Discrete Fourier Transformation (DFT). After DFT, the integrated spectral density within a certain frequency window represents the power (or variance) of the signal for that specific frequency window. However, heart period time series may be transformed into power spectra by other techniques as well. Discrete Wavelet Transformation (DWT) is a relatively new technique and has been an important topic in mathematics, science, engineering,
Comparison between the Fourier and Wavelet methods

and (more recently) economics. An extensive introduction to Wavelets and its applications can be found in Chui (1992). Usage of DWT for analyzing heart period variability has been described by Akay, Landesberg, Welkowitz, Akay, and Sapoznikov (1993), Pichot and co-workers (1999), and Wiklund, Akay, and Niklasson (1997). Wavelets allow simultaneous decomposition of a time series into components that are localized in both time and frequency. This is unlike Fourier transformation where the obtained components are localized in the frequency domain only, and all time domain information is lost. By multiple convolution steps with a pre-determined Wavelet base function, a time series can be transformed into several new levels of time series, with each level representing frequencies within a specified frequency window. The widths of the frequency windows and the number of points representing the original time area both vary with each convolution step. For DWT, an input signal of $2^n$ data points will be transformed with $n$ convolution steps into a constant and $n-1$ time series. The higher the frequency, the more Wavelet coefficients needed for that level to represent the signal within the original time interval. After DWT, the power can be calculated for each frequency window by summing the squares of the coefficients at that level. The selection of the Wavelet base that should be used for a data set is important since the DWT coefficients are a function of both the original data and the Wavelet base. Therefore, the selected base should 'match' the original data set.

To summarize, DWT may be used to calculate power values for specific frequency bands (analogous to DFT), without any assumption of stationarity, and it also offers some additional information that may be used to obtain an impression of how these power values fluctuate over time. Formulas of the DWT decomposition and reconstruction algorithms are shown in the appendix.

Pichot and co-workers (1999) analyzed the same heart rate variability data both with the DFT and the DWT methods. Fourier and Wavelet transforms were computed from sequences of heart period intervals of six participants receiving increasing doses of atropine and propranolol. Their results demonstrated that power values obtained from the Wavelet transform gave a significantly better quantitative analysis of heart period variability than did power values obtained from the Fourier transform. Differences between the doses were more pronounced after Wavelet transformation.

We cannot conclude from the results of Pichot and co-workers (1999) whether differences between power values obtained by both methods are due to violations of the assumption of stationarity when the Fourier method is used, because they did not test their IBI data for stationarity. The Fourier method of spectral analysis assumes that the data show at least weak stationarity. The issue of non-stationarity has been discussed in detail elsewhere by several authors (Berntson et al., 1997; Grossman, 1992; Porges & Bohrer, 1990; Weber, Molenaar, & van der Molen, 1992a; Weber, Molenaar, & van der Molen, 1992b). The stationarity test of Weber and co-workers (1992a,1992b) is derived from evolutionary spectral analysis and is a modification of the test described by Priestley and Subba Rao (1969).
and co-workers (1992a, 1992b) proposed the idea of testing for non-stationarity, and to select (sub-) segments that were classified as stationary for further analyses.

In the present study we attempt to answer the question whether a spectral analysis method without any assumption of stationarity should be used for psychophysiological heart period variability studies. For this purpose, a quantification is needed of the error that is made by violating the assumption of stationarity when DFT analysis is used for spectral decomposition of heart period power. A typical (stress-reactivity experiment) heart period data set is used to compare power values obtained by the DFT method and power values obtained by the DWT method. Such a comparison is done separately for stationary and non-stationary segments. We expect that the differences between both methods are greater for non-stationary segments. An ambulatory monitoring device is used to measure the heart period data. We have chosen to employ a within-subjects design with a laboratory psychological stress task followed by a rest period outside of the laboratory. Such a design is expected to produce many stationary as well as non-stationary data segments, even when the data are controlled for physical activity.

Method

Participants
The 40 participants were 15 male and 25 female healthy, first year psychology students from the University of Amsterdam, aged 18-32 years ($M=21.6$, $SD=3.2$). All participants received course credits for participation and prizes could be won for the two best performers on the task (Hfl 50 ($$27) and Hfl 25 ($$14)). None of the participants used medication (except contraceptives). Participants refrained from eating, drinking (except water), smoking, and physical exercise one hour prior to the commencement of the experiment. Participants were randomly assigned to one of two conditions which were different in the stress task manipulation.

Apparatus
A MS-DOS computer with two external buttons was used for the psychological stress task. The task consisted of an intelligence test with real time performance feedback combined with a reaction time task. The intelligence test questions were presented on the center of the screen. The reaction time task (used to distract the participant when performing the intelligence test) consisted of randomly-timed, falling red and green coins that were presented on both the left and right sides of the screen. Participants were instructed to press the left button when a green coin was falling on the left side, and to press the right button when a green coin was falling on the right side. A combined score of the performance on both tasks was
Comparison between the Fourier and Wavelet methods

continuously presented to the participant who was informed about what limit should be reached to be in competition for the prizes.

The physiological measurements were made with the Vrije Universiteit Ambulatory Monitoring System (VU-AMS) version 4.3. This device uses six Ag/AgCl electrodes to record IBI's and thoracic impedance (dZ), and also gives an indication of the amount of physical activity (motility). Details on electrode placement and R-spike detection of this device can be found in de Geus and co-workers (1995). Cross-instrumental comparison of the VU-AMS with a standard laboratory measurement set-up showed excellent between-subjects and within-subjects correlation of respiration rate, Respiratory Sinus Arrhythmia (RSA), and spectral heart period powers (de Geus et al., 1995).

Procedure
A combined laboratory-ambulatory design was used. Moments of psychological stress in the laboratory were alternated with relaxing moments outside the laboratory. The measurement period always started and ended at 1 PM and 4 PM respectively. After instruction and informed consent, the ambulatory recording equipment was attached to the participants. Next, they spent approximately 30 minutes in the laboratory, during which time they were in seated position in front of the computer. Half of the participants performed the psychological stress task first (which took approximately 15 minutes), while the other half sat in front of a blank computer screen and waited for 15 minutes. After this initial period in the laboratory, participants were brought to another waiting room for a 65-minute break, during which time they were able to sit down, relax, and read. Following this break, participants were brought back to the laboratory where all of them performed the psychological stress task. Because half of the participants performed this task for the second time, it consisted of a parallel version of the task used in the first session. Afterwards, the participants were again brought back to the waiting room for a further break of 55 minutes. During the measurement period, there were also five separate moments when participants were asked to complete a number of questionnaires and then provided saliva samples (results not reported here).

Data analysis
The total interval of recorded physiological data for each participant was nearly 3 hours. These data were analyzed in segments representing 128 seconds. The segments had an overlap in time of 1 minute. This overlap was created because it increased the probability that stationary and non-stationary segments represented

1. The analysis software, that we developed for this study, can be downloaded from www.psy.vu.nl/vu-ams/software/software.ptfap.html.
the same time periods and experimental situations. Data segments with a measured vertical acceleration motility value above 0.6 gsec were discarded from the analyses. This threshold value distinguished (for our VU-AMS device) segments with quiet sitting from segments with walking or turning.

An artifact pre-processing was performed on the IBI data by detecting outlier IBI values (above 1800 ms or below 300 ms thresholds, and by visual inspection). Since artifacts cannot simply be deleted, because then the continuity of the time is lost, spuriously short IBI’s were summed and missing beats were ‘created’ by splitting spuriously long IBI’s. In practice, as visual inspection demonstrated, the VU-AMS R-spike detection works very reliably and correction of IBI data appeared to be quite rare.

IBI segments (representing time intervals of 128 seconds) were selected, from which the IBI mean and variance values were computed.

The stationarity of each IBI data segment was determined by using the stationarity algorithm of Weber and co-workers (1992a,1992b). Since this study requires stationary and non-stationary segments to be equal in length, combined with the fact that the data segments already have an overlap in time, the stationary sub-segment search algorithm of this test was switched off. A Chi-square value was computed by this test (for each segment), indicative of the degree of non-stationarity (see Weber, 1992a). The nominal alpha value was set to .01 to classify a segment as stationary or non-stationary.

Uniformly spaced samples were created by interpolation of the IBI data segments using a Wavelet interpolation algorithm with a quadratic spline as base. Sets of 256 IBI’s were first refined in four back-wards convolution steps and then low-pass filtered by a Wavelet filter (1 Hz). This procedure resulted in a 16-fold refinement of the IBI data set. In this interpolated IBI data series, new samples were taken at uniformly spaced time intervals (62.5 ms). The first 2048 newly created samples were taken as data segment to be further analyzed, corresponding with 2048*62.5 ms = 128 sec. A sample time of 62.5 ms (16 Hz) combined with 2048 samples was selected to match the frequency bands after DWT with the requested LF and HF heart period variability frequency bands (see below). These values result in segment lengths of 128 seconds, which is long enough to get a reliable indication of the powers in the LF and HF bands (see Berntson et al., 1997). Although, as stated by Berntson and co-workers (1997), reliable estimation of the lowest frequency powers in the ULF band requires a segment length longer than 128 seconds, the ULF power values were also computed for (exploratory) comparison.

The uniformly spaced data segments were cosine-tapered, DFT transformed, smoothed, and the summated powers for the ULF band (below 0.0625 Hz), LF band (0.0625 - 0.125 Hz), and the HF band (0.125 - 0.5 Hz) were computed. The small differences between our frequency bands and values regularly used in the literature were necessary to make them comparable with the bands obtained after DWT transformation. Next, the uniformly spaced data segments were Wavelet
transformed with the DWT algorithm using a cardinal cubic spline function as base (Chui, 1992, appendix). This base was chosen since it performed in a superior manner to several other orthonormal bases when we attempted to re-establish the exact original signal in the time domain after reconstruction transformation. Frequency-specific time series were created from the DWT transformed data by reconstruction transformation after zeroing all coefficients that represented frequencies outside the requested window. Next, the statistical variance of each frequency-specific time series was derived as an indication of the power within this frequency band. The ULF power was computed as the sum of the variances below 0.0625 Hz, the LF power was computed as the variance of the 0.0625 - 0.125 Hz window, and the HF power was computed as the sum of the variances of the 0.125 - 0.25 Hz and 0.25 - 0.5 Hz windows. Note that the size of a frequency window always doubles after each Wavelet decomposition step. Since the DWT (like DFT) suffers from aliasing effects at both ends, the first and last 40 data points (2.5 sec) of the time series were excluded from the derivation of the variances.

The DFT and DWT methods of analysis were compared by computing (for each participant and frequency band) the pearson product-moment correlation (PMCC) between the log-transformed powers across the segments. Next, the within-subjects mean and standard deviation values were computed (across the segments) for the differences between the log-transformed powers obtained by both methods. These mean and standard deviation values (for each participant and frequency band) were computed separately for stationary and non-stationary segments. Finally, the differences between these stationary and non-stationary mean and standard deviation values were tested (across subjects) with paired t-tests.

Results

Mental stress manipulation
The within-subjects mean heart period during the first session in the lab ($M=0.79, SD=0.11$) was compared with the mean heart period during the first resting moment ($M=0.92, SD=0.14$). The mean heart period time was significantly lower during the lab session than during rest, $T(39)=9.19, p<.001$.

Data example of one randomly chosen participant
Figure 1 shows the IBI data for a non-stationary segment (128 sec) of one of the participants during rest. The corresponding power spectrum of these data (computed with the DFT method after creation of uniformly spaced samples) is displayed in Figure 2. Figure 3 shows the same (uniformly spaced) data segment
(shown at the top) and seven frequency-specific time series computed from this with the DWT method as described above. Summing these seven time series exactly reproduces the original data (shown at the top) again. Figures 4a, 4b, and 4c show the scatter plots between log-transformed powers obtained by the DFT and DWT methods for the ULF, LF, and HF bands.

![IBI data for a segment classified as non-stationary](image1.png)

**Figure 1.** IBI data for a segment classified as non-stationary

![DFT power spectrum of the IBI data shown in Figure 1](image2.png)

**Figure 2.** DFT power spectrum of the IBI data shown in Figure 1

**Comparison between the DWT and DFT methods of data analysis**

**Correlation values.** For each participant the PMCC correlations between log-transformed power values obtained by the DWT method and log-transformed power values obtained by the DFT method for the ULF, LF, and HF bands were calculated. The mean correlations (across the participants) are presented in Table 1. All these within-subjects correlation values were very high and significant for each participant (all p’s < .01).
Comparison between the Fourier and Wavelet methods

Figure 3. Equidistant sampled time series (top) of the IBI data shown in Figure 1 and the frequency specific time series that were computed from this data using the DWT method.

Comparison of the mean values of differences. The mean values (across the participants) of the within-subjects mean values of the differences between the log-transformed DWT and DFT powers are presented in Table 1. Note that these differences were always smaller than 1 percent of the mean computed power values. One-sample t-tests revealed a significant difference of these mean difference values from zero for the ULF band, $T(39)=-17.32$, $p<.001$, for the LF band, $T(39)=3.72$, $p<.001$, and for the HF band, $T(39)=17.29$, $p<.001$. Power values computed by DWT were smaller for the ULF band, but larger for the LF and HF bands. Paired t-tests were used to test for differences (of the difference between both methods) between stationary and non-stationary segments. These tests revealed no significant differences between stationary and non-stationary mean values for the ULF band, $T(39)=1.82$, $p=.076$, the LF band, $T(39)=-0.55$, 
Chapter 3

$p = .587$, and the HF band, $T(39) = 0.151$, $p = .881$. However, these results do not exclude that the mean standard deviation values of the within-subjects differences between both methods may be lower for stationary segments as compared to non-stationary segments.

![Figures 4a, 4b, and 4c.](image)

Scatter plots for one participant showing the similarity of the ULF, LF, and HF powers obtained by the DWT method and the DFT method.

Comparison of the standard deviation values of differences. The mean values (across the participants) of the within-subjects standard deviation values of the differences between the log-transformed DWT and DFT powers are presented in Table 1. One-sample t-tests revealed a significant difference of these mean standard deviation values from zero for the ULF band, $T(39) = 22.78$, $p < .001$, for the LF band, $T(39) = 34.95$, $p < .001$, and for the HF band, $T(39) = 17.95$, $p < .001$. These results are indicative of non-homogeneous differences between the powers.
Comparison between the Fourier and Wavelet methods

computed by both methods for all bands. Paired t-tests revealed no significant difference between stationary and non-stationary mean standard deviation values for the ULF band, $T(39)=-0.93$, $p=.927$. However, a significant difference was found for the LF band, $T(39)=2.06$, $p<.05$, and for the HF band, $T(39)=5.36$, $p<.001$. For these frequency bands, the mean standard deviation values of the within-subjects differences between both methods were lower for stationary segments (as expected).

Table 1. Mean and standard deviation values across the participants ($n=40$) for the number of segments, the within-subjects correlations across the segments, the within-subjects means across the segments, the within-subjects mean differences across the segments, and the within-subjects standard deviations of the differences across the segments between the log-transformed power values obtained by the DWT method (WHF,WLF,WULF) and the DFT method (FHF,FLF,FULF).

<table>
<thead>
<tr>
<th></th>
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<tr>
<td></td>
<td>$M$</td>
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<td>$SD$</td>
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<tr>
<td>$r(\text{WHF,FHF})$</td>
<td>.9824</td>
<td>.0225</td>
<td>.9843</td>
<td>.0156</td>
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<td>.0195</td>
<td>.9577</td>
<td>.0204</td>
</tr>
<tr>
<td>$r(\text{WULF,FULF})$</td>
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<td>.0033</td>
<td>.9951</td>
<td>.0026</td>
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<tr>
<td>$\text{Mean}((\text{WHF}+\text{FHF})/2)$</td>
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<td>0.40</td>
<td>3.11</td>
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<tr>
<td>$\text{Mean}((\text{WLF}+\text{FLF})/2)$</td>
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<td>0.34</td>
</tr>
<tr>
<td>$\text{Mean}((\text{WULF}+\text{FULF})/2)$</td>
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<td>0.28</td>
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<td>0.31</td>
</tr>
<tr>
<td>$\text{Mean}(\text{WHF-FHF})$</td>
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<tr>
<td>$\text{Mean}(\text{WULF-FULF})$</td>
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<tr>
<td>$\text{SD}(\text{WHF-FHF})$</td>
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<td>0.0119</td>
<td>0.0315</td>
<td>0.0123</td>
</tr>
<tr>
<td>$\text{SD}(\text{WLF-FLF})$</td>
<td>0.0727</td>
<td>0.0122</td>
<td>0.0682</td>
<td>0.0133</td>
</tr>
<tr>
<td>$\text{SD}(\text{WULF-FULF})$</td>
<td>0.0275</td>
<td>0.0086</td>
<td>0.0276</td>
<td>0.0067</td>
</tr>
</tbody>
</table>

Note: The percentage values of the mean $(W-F)$ power differences, related to the pooled $(W+F)/2$ power values, are respectively 0.65%, 0.29%, and 0.48% for the non-stationary HF,LF,ULF segments, and 0.65%, 0.33%, and 0.54% for the stationary HF,LF,ULF segments.
Discussion

Inter- and intra-individual comparison demonstrated high mean correlation values (> .95) and small mean differences (< 1%) between heart period power values obtained by the DFT method and power values obtained by the DWT method. As hypothesized, larger differences between both methods were found for segments that were classified as non-stationary. However, these differences were surprisingly small and more pronounced for the higher frequencies.

For the conditions and settings of this study (a typical stress-reactivity experiment), conclusions based on frequency-specific mean heart period powers using the DFT method (without controlling for stationarity) are probably not very different from conclusions based on the DWT method. Only when very small effects have to be demonstrated (as in the study of Pichot and co-workers, 1999), using DWT can prove beneficial.

The mean heart period interval times were much lower during the sessions in the lab than during rest in the waiting room. It can be concluded from this that the emotional stress manipulation had been successful and that the within-subjects change in heart period over time was large enough to warrant a comparison between both data analysis methods.

The selected motility threshold for rejecting data segments was set at a value (specific for our VU-AMS device) that resulted in the discarding of all periods of walking, turning, and moving. This threshold-level makes our conclusions comparable with most experimental situations where movements are strictly controlled for. It should be noted that the differences between the DWT and DFT methods of spectral analysis might have been larger if the selected motility threshold-level was not as strict. Intuitively, segments with more motility are expected to have a higher degree of non-stationarity. This implies that the need for a method of analysis without the assumption of stationarity (like the DWT method) is probably larger when heart period data from ambulatory studies are to be analyzed.

The choice in this study of relatively short data segments (128 seconds) might have influenced our conclusions as well. Although the lowest frequency powers in the ULF band could not be reliably estimated by the chosen segment length of 128 seconds (Berntson et al., 1997), both methods produced similar estimations for the mean power values of the ULF band. Longer segments would have produced more reliable estimations of the ULF band powers, but they have a higher risk of failing the stationarity test. Thus, more segments would be classified as non-stationary when the segment length increases. This problem can be resolved by using the method of Weber and co-workers (1992a, 1992b). This method implies selection of stationary sub-segments for computation of the heart period power values. However, a comparison between power values computed from sub-segments by the DFT method and power values computed from the original segments by the DWT method results in larger differences, because the selected stationary sub-
Comparison between the Fourier and Wavelet methods

segments of data are no longer representative of the original data (see Grossman, 1992). For longer data segments, an improved solution can be found by using the DWT method applied to the entire non-stationary segments.

Grossman, van Beek, and Wientjes (1990) compared three quantification methods that are in use for estimating RSA. These methods were: (a) the ‘peak to valley time domain method’, (b) the ‘Fourier transformation method’ and (c) a complex de-trending procedure called the ‘moving polynomial method of Porges’. They concluded that a very close comparability exists between the three different estimates of RSA and that none of the methods evaluated could claim to produce an obviously superior index of RSA. Our results are in harmony with this conclusion in that the DWT and DFT methods performed surprisingly similar for computation of the heart period power values.

We are, nonetheless, convinced that the DWT method, not the DFT, is the theoretically valid method to use with non-stationary data. Heart period data are clearly non-stationary. Hence, it is especially surprising that the DFT method yielded results comparable with the DWT method for heart period data produced by a typical stress-reactivity experiment. The DWT method appears only to be superior for analysing these data when additional analyses in the time-frequency domain are required.

An example of how this additional information in the time-frequency domain can be used in the interpretation of the DWT transformed data is given by Ivanov and co-workers (1996). They observed the distribution of the amplitudes of the variations in the beat to beat signal corresponding with a specific frequency. This was achieved by fitting specific probability distribution functions to these distribution data and by comparing these fitting parameters between participants.

Another way of using the additional time-frequency information produced by the DWT transformed data (probably more of relevance for RSA) is to observe the patterns of variation in time series together with a time synchronous time series of another signal. When the respiration and heart period signals are both DFT transformed, the coherence can be computed as a measure of the transfer from respiration to heart rate. Although this technique works for stationary data, it probably does not result in a stable coherency spectrum when the data are non-stationary. However, the coupling between two signals for specific frequency intervals can also be estimated by the DWT method. For this method, both signals should first be transformed to several time series by Wavelet transformation (each representing a certain frequency window as described above). Next, an impression of the (non-stationary) transfer can be obtained simply by calculating the square of the maximal cross-correlation for each (frequency window specific) set of time series. The lag of the maximal cross-correlation gives an impression of the phase shift between the respiration and heart period signals for that specific frequency window. Thus, the additional time-frequency information produced by the DWT method can be used for obtaining a non-stationary index of coupling between heart period data and respiration.
Finally, DWT transformation can also be used for data reduction or smoothing, by respectively selecting coefficients above a certain quantile-threshold or reducing the amplitude of coefficients representing unwanted frequencies. Wavelet data reduction or smoothing is able to eliminate rapid oscillations in the signal, but without eliminating sharp turns with a lower base frequency. In general, Wavelet transformation can be used as a filter by making all coefficients representing a certain frequency window equal to zero (or by reducing the amplitudes) before inverse transformation. This filter has an advantage over using the Fourier transform for filtering since no information from the signal in the time domain is lost (there is no assumption of stationarity).

In summary, it can be concluded that for a typical stress-reactivity experiment, mean heart period powers computed by the DFT method (without controlling for stationarity) are only marginally different from mean powers computed by the DWT method. Differences between these methods are partially the result of the error that is made by violating the assumption of stationarity when the DFT method is used. Because the differences are surprisingly small, the DWT method is only superior for analysing heart period data when additional analyses in the time-frequency domain are required.

Appendix

The DWT formulas:

DWT decomposition algorithm:

\[
c_{i}^{j-1} = \sum_{k} a_{i-2k} c_{i}^{j}
\]

\[
d_{i}^{j-1} = \sum_{k} b_{i-2k} c_{i}^{j}
\]

\[
d_{i}^{N-1} \rightarrow d_{i}^{N-2} \rightarrow \ldots \rightarrow d_{i}^{N-M}
\]

\[
c_{i}^{N} \rightarrow c_{i}^{N-1} \rightarrow c_{i}^{N-2} \rightarrow \ldots \rightarrow c_{i}^{N-M}
\]

\[a_{k}, b_{k} = \text{wavelet decomposition sequences}\]

DWT reconstruction algorithm:

\[
c_{i}^{j} = \sum_{k} [p_{k} c_{i}^{j} + q_{i-2} d_{i}^{j-1}]
\]

\[
d_{i}^{N-M} \rightarrow d_{i}^{N-M+1} \rightarrow \ldots \rightarrow d_{i}^{N-1}
\]

\[
c_{i}^{N} \rightarrow c_{i}^{N-1} \rightarrow \ldots \rightarrow c_{i}^{N-M}
\]

\[p_{k}, q_{k} = \text{wavelet reconstruction sequences}\]

Note: The DWT Decomposition algorithm starts at the largest hierarchy and works towards the smallest (from Chui, 1992, 5.4.48). The DWT Reconstruction algorithm starts at the smallest hierarchy and works towards the largest (from Chui, 1992, 5.4.49).
Acknowledgements

We thank Constance Handforth, Iriet Pappie, and Michel Slinger for their assistance in the experimental phase.

References


Differential contribution of cardiac vagal tone, central respiratory drive, and respiratory parameters to RSA during mental stress and physical exercise

Jan H. Houtveen, Simon Rietveld, & Eco J. C. de Geus

Abstract

Changes in Respiratory Sinus Arrhythmia (RSA) may result from changes in Cardiac Vagal Tone (CVT), Central Respiratory Drive (CRD), tidal volume, and respiratory frequency. The differential contribution of these parameters to RSA during different stressors is not clear, which hampers the interpretation of reduced RSA found in high risk or patient groups. This study tested the contributions of these determinants to RSA in a within-subject design. Twenty-two healthy participants were submitted to mental stress, relaxation, and mild physical exercise during three different breathing conditions: normal breathing, breathing compressed room air, and breathing compressed 5% CO₂-enriched air. The CO₂-enriched air was used to manipulate CRD, which was estimated with the end-tidal partial pressure of CO₂ (PetCO₂). RSA was measured as high frequency heart period variability power. Respiratory parameters were derived from the thoracic impedance signal. The Pre-Ejection Period (PEP) was measured to obtain an indication of changes in the cardiac sympathetic control, and used in combination with changes in heart rate to estimate changes in CVT. Path-analysis demonstrated that changes in CVT, CRD, and respiratory depth and frequency each had an independent contribution to changes in RSA. Reductions in RSA were enhanced by increases in respiratory frequency and reduced by increases in CRD and respiratory depth. The relative contributions of these determinants were different for mental stress and physical exercise. To index within-subject changes in CVT, changes in RSA should be corrected for changes in PetCO₂, tidal volume, and respiratory frequency.
Introduction

Heart period variability that is related to respiration is known as Respiratory Sinus Arrhythmia (RSA). Between-subject clinical studies have demonstrated that reduced RSA is associated with cardiac disease (Hayano et al., 1991; Kleiger, Miller, Bigger, & Moss, 1987; Lombardi et al., 1987; Martin et al., 1987; Saul et al., 1988; Singer et al., 1988), hypertension (Julius, Pascual, & London, 1971; Mallani, Pagani, Lombardi, Guzzetti, & Cerutti, 1991), anxiety (Thayer, Friedman, & Borkovec, 1996; Watkins, Grossman, Krishnan, & Sherwood, 1998), and depression (see Musselman, Evans, & Nemeroff, 1998). Within-subject psychophysiological studies have demonstrated that psychological stress (Allen & Crowell, 1989; Kamphuis & Frowein, 1985; Langewitz & Ruddel, 1989) and physical exercise (Hatfield et al., 1998; Tulppo, Mäkikallio, Kakala, Seppanen, & Huikuri, 1996) reduce RSA, while increased RSA is associated with conditions of psychological relaxation (Skakibara, Takeuchi, & Hayano, 1994). Thus, RSA is now widely considered of great importance in both fundamental and clinical (psycho)physiological research. A major point of discussion, however, is the interpretation of RSA as an index of central ‘cardiac vagal tone’, a concept that is often not specified in any detail. Independently of changes in cardiac vagal tone, rapid low-tidal volume breathing will reduce the degree of RSA, while slow high-tidal volume breathing will increase RSA (Allen & Crowell, 1990; Grossman, Karemaker, & Wieling, 1991; Grossman & Kollai, 1993; Kollai & Mizsei, 1990; Saul, Berger, Chen, & Cohen, 1989). In addition, Al-Ani, Forkins, Townend, and Coote (1996) have demonstrated that, independently of the changes in breathing pattern, changes in the central respiratory drive can also influence RSA.

In this paper, RSA is defined to result from the phasic changes in vagal nerve activity at the cardiac sino-atrial node that are linked to the respiratory frequency. Cardiac vagal tone is defined as the basal (tonic) firing rate of the cardiac vagal motor neurons located at the Nucleus Ambiguus (NA). This tonic firing rate of the NA motor neurons (i.e., which Porges (1995) described as the ‘smart’ vagus) is influenced by central projections including those from amygdalar and hypothalamic (e.g., the paraventricular nucleus) regions, and by projections from other brain stem nuclei (e.g., the nucleus tractus solitarius). As in the model of Berntson and co-workers (Berntson, Cacioppo, & Quigley, 1993; Berntson et al., 1997) we assume that this tonic vagal firing is modulated with a respiratory-related phasic signal by the output of the central respiratory generator (see also Porges, 1995 and Taylor, Jordan, & Coote, 1999).

The output of the central respiratory generator is regulated by several complex mechanisms of which two chemo-reflex mechanisms (based on O₂ and CO₂ receptors) are the most important (Feldman & McCrimmon, 1999). Al-Ani and co-workers (1996) compared RSA during increased respiratory activity (respiratory frequency, depth of breath) evoked by (a) inhalation of 5% CO₂-
enriched air, and (b) voluntary increased breathing. The authors argued that the voluntary command to breathe bypasses the central respiratory generator to have its main effect directly on the spinal respiratory motor-neuron pools. Results showed that RSA was greater during CO₂-enriched air inhalation than during voluntary hyperventilation (with similar depth and respiratory frequency). The CO₂-effect was even more pronounced when the muscarinic M1 antagonist scopolamine was administrated to enhance the vagal output to the heart. These results suggest that RSA can be influenced by changes in the central respiratory drive, independently of the cardiac vagal tone and actual respiratory behavior. The tonic vagal firing rate of the NA motor neurons may be further modulated by a peripheral pulmonary stretch-reflex mechanism and by respiratory linked changes in baro-reflex activity (Berntson et al., 1993; Taylor et al., 1999). Empirically, baro-reflex and chemo-reflex related changes in RSA have indeed been reported (see Al-Ani et al., 1996). Finally, RSA decreases as the respiratory frequency increases as a result of a progressive decline in the frequency-transfer function of the cardiac vagal innervation (Eckberg, 1983; Berntson et al., 1993).

In short, four major determinants of changes in RSA are recognised: (a) cardiac vagal tone or the basal firing rate of the NA motor neurons, (b) the central respiratory drive, (c) peripheral respiratory-related feedback from the baro-reflex and the pulmonary stretch-reflex, and (d) the vagal-cardiac frequency transfer function. Although these four determinants to RSA may be coupled during mental stress and exert a mutually enhancing influence on a reduction of RSA (lower cardiac vagal tone, lower central respiratory drive, lower tidal volume, higher frequency), they may be dissociated during other conditions (e.g., exercise) and/or in specific clinical groups. The present study aimed to examine the balance of the contributions of these determinants to RSA during relaxation, mental stress, and physical exercise. It required, therefore, that these four RSA determinants were estimated and manipulated.

Cardiac vagal tone: How to non-invasively manipulate and/or assess cardiac vagal tone without using RSA itself? Using dual blockade as was done in the exemplary study of Berntson, Cacioppo, Quigley, and Fabro (1994) was not considered feasible, because of the unpredictable effects of cholinergic and adrenergic blockade on respiratory drive and behavior, specifically during CO₂ breathing. As an alternative, we started with the established fact that stress and exercise both reduce cardiac vagal tone. We then made a crucial assumption that in a within-subject design, the stressor-induced changes in cardiac vagal tone from the NA are linearly reflected in tonic changes in heart rate level after a correction for the changes in tonic cardiac sympathetic effects. However, this introduces two sources of error. Firstly, interactive effects of cardiac sympathetic and parasympathetic nerves are left unaccounted. Although previous studies suggest that the interactive effects would probably not be substantial in the physiological range of our manipulations, they are not zero (Berntson et al., 1994; Levy, 1997).
Secondly, changes in heart rate caused by an independent second cardiac vagal pathway that has its origin in the Dorsal Motor Nucleus (DMNX) are also left unaccounted. Although this DMNX vagal contribution to heart rate is not reflected in RSA (Porges, 1995), it might (differentially) influence the absolute heart rate response to stress and exercise. To estimate cardiac sympathetic effects (including effects of circulating catecholamines), the Pre Ejection Period (PEP) was used. Although absolute PEP-values may be hard to interpret, within-subject changes in PEP reflect changes in myocardial contractility, which is commonly interpreted as a sensitive index of sympathetic cardiac effects (Sherwood et al., 1990).

Central respiratory drive: The experiment of Al-Ani and co-workers (1996) suggests that increased arterial partial pressure of CO$_2$ (PaCO$_2$), either through respiratory arrest or artificial inhalation of CO$_2$-enriched air, is able to enhance the central respiratory drive. Thus, 5% CO$_2$ breathing can be used to manipulate the central respiratory drive, and an estimation of the PaCO$_2$ (e.g., with the end-tidal partial pressure of CO$_2$ (PetCO$_2$)) can be used to quantify changes in its strength. However, because the 5% CO$_2$-enriched air mixture has to be inhaled from compressed air, an additional control condition is desirable in which participants inhale compressed room air under the same conditions as they inhale 5% CO$_2$-enriched air.

Baro-reflex and pulmonary stretch-reflex: Although both reflex loops are complex and only partially understood, the effects of the baro-reflex and stretch-reflex on RSA are due to changes in either tidal volume or respiratory frequency (Berntson et al., 1993). Therefore, changes in tidal volume and respiratory frequency can be used to estimate the extent of cardiac vagal tone modulation through these peripheral respiratory-related feedback mechanisms. The classical approaches to the combined measurement of respiratory parameters include intrusive techniques like spirometry and pneumotachography, or indirect estimation by means of nose clip thermistors. The present study, which employed 5% CO$_2$-enriched air breathing, did not allow for the use of intrusive measurement or nose thermistors. Instead we used the continuous thoracic impedance (dZ) signal. Recent studies from different groups (De Geus, Willemsen, Klaever, & van Doornen, 1995; Ernst, Litvack, Lozano, Cacioppo, & Berntson, 1999) have shown that, after appropriate band-pass filtering, thoracic impedance can be used to obtain a reliable index of respiratory frequency. Furthermore, in a within-subject design, the spectral power of the filtered thoracic impedance signal can be used as an approximation of changes in respiratory depth.

Frequency-transfer function: During expiration, sinoatrial ACh release from cardiac vagal nerves increases, and during inspiration it decreases. Whether these fluctuations in ACh release fully reflect respiratory related changes in heart rate, will strongly depend on the respiratory frequency. Slow changes in cardiac vagal firing will have a more full impact than faster changes on the difference between
the longest beat in expiration and the shortest beat in inspiration. In the normal breathing range these filter characteristics of the muscarinergic synapse have been shown to yield a fairly linear decrease in RSA with increasing respiratory frequency (Eckberg, 1983). Based on this relationship, various studies have already used the respiratory frequency as a covariate when using RSA as an index of cardiac vagal tone in both within-subject and between-subject comparisons (Allen & Crowell, 1990; Kollai & Mizsei, 1990; Grossman, Karemaker, & Wieling, 1991; Grossman & Kollai, 1993; Grossman & Wientjes, 1986; Kollai & Mizsei, 1990; Kollai & Kollai, 1992; Saul, Berger, Chen, & Cohen, 1989).

Within the perspective outlined above, the contributions of within-subject changes in cardiac vagal tone, central respiratory drive, and respiratory parameters to within-subject changes in RSA can be estimated using the change (Δ) scores of Interbeat Interval (IBI), change scores in PEP, change scores in PetCO₂, change scores in respiratory depth, and change scores in respiratory frequency. A path diagram of this model is shown in Figure 1.

![Path diagram](image)

**Figure 1.** Path diagram depicting all contributions to changes in RSA. (Note that it is intuitively not immediately apparent why cardiac vagal tone is made to influence RSA through both IBI and PEP in this path diagram. This is clarified in the equations in the appendix).

Two main hypotheses were tested with this study: (1) each of the four determinants has a significant influence on RSA, and (2) their relative
contributions may vary across stressors (or situations). To demonstrate situation-specificity, RSA and its determinants were assessed during mental stress and physical exercise. During exercise the PaCO₂ (related to the central respiratory drive) increase and, as a result, the respiratory frequency and depth also increase (see Feldman & McCrimmon, 1999). However, during mental stress the PaCO₂ is more likely to decrease than to increase, while the respiratory activity generally increases (Grossman, 1983; Wientjes, 1992). Thus, the contributions of changes in the central respiratory drive and respiratory activity on changes in RSA are different during mental stress compared to physical exercise. For an optimal comparison of the two conditions, we real-time adjusted the load during exercise for each participant, to obtain the identical heart rate response during physical exercise as was found during mental stress. The relaxation condition was used as a general baseline. Better understanding of the relative contribution of the determinants to RSA in various conditions should improve future interpretation of deviating RSA responses in high risk and patient groups.

**Methods**

**Participants**

There were 30 young adults without chronic disease or health complaints invited to participate, of which 8 were excluded because they were unsuccessful in maintaining their heart rate within the requested range during the (mild) physical exercise task. The final sample consisted of 11 men (age M=24.0, SD=5.9) and 11 women (age M=20.3, SD=1.1). The study was presented as investigation of breathing patterns. The participants believed that they could win 100 Dutch guilders ($50), although all received a similar amount of 30 Dutch guilders ($15) after the experiment. All participants signed an informed consent. The study had been approved by the ethics committee of the department of Psychology, University of Amsterdam. None of the participants used medication excepting oral contraceptives in seven women. The participants were instructed to refrain from eating, drinking (except for water), smoking, or physical exercise within one hour before the experiment.

**Procedure**

The experiment consisted of three conditions that were conducted in fixed order: (1) a mental stress task, (2) a ‘relaxation’ condition, and (3) mild physical exercise. Each of these conditions consisted of three parts of 4 minutes each, again conducted in fixed order: (a) breathing normally, (b) breathing compressed room air through a face mask, and (c) breathing compressed 5% CO₂-enriched air
through a face mask. All experimental sessions took place between 11 AM and 4 PM, and lasted approximately 2.5 hours.

After general instructions, the recording electrodes were attached and connected to the Vrije Universiteit Ambulatory Monitoring System (VU-AMS version 4.3; see below). Next, the participants went into a waiting room for 15 minutes to relax, during which they were quietly sitting and read a popular magazine. Next, they entered the experimental room that was sound shielded and dimly lit. The VU-AMS was connected to an MS-DOS computer, and the participants were attached to the PetCO₂ recording equipment (see below). Next, the mental stress task was started on the MS-DOS computer. Intelligence test questions were presented one by one on the middle of the screen. The maximum time for each question was 60 seconds and the elapsed time was visible on screen. The participants selected one of five multiple-choice responses (1 to 5) and pressed the corresponding key on the PC-keyboard. A simultaneously presented reaction time task consisted of random timed falling red and green coins on the left and right side of the screen. The participants were instructed to press the left button (located at the left side of the keyboard) when a green coin was falling on the left side, and to press the right button (located at the right side of the keyboard) when a green coin was falling on the right side. The computer acknowledged each response (or lack of response) with a brief auditory signal: a musical tone indicating a correct response and a low frequency buzz indicating error. The combined score on the intelligence and reaction time tasks was expressed in Dutch guilders on the screen. The initial amount was 100 Dutch guilders ($50), which gradually diminished as a result of the errors made. Real bank notes were placed in front of the participants before the task started, and withdrawn when lost. Two research assistants observed the participants and their performance at close range to increase the stressfulness of the task. After 4 minutes, participants (additionally) had to breathe compressed room air through a face mask (4 minutes), and breathe compressed CO₂-enriched air through a face mask (4 minutes). Next, the PetCO₂ recording equipment was disconnected and the participants were debriefed about the stress induction and accompanied to the waiting room.

After a new 15 minute period of quiet sitting and reading, the participants re-entered the experimental room for the ‘relaxation’ condition. The VU-AMS was again connected to the MS-DOS computer and the participants were again attached to the PetCO₂ recording equipment. This condition was not different from the previous relaxation (i.e., the participants quietly sat reading a popular magazine) but after 4 minutes, they (additionally) had to breathe compressed room air through a face mask (4 minutes), and breathe compressed CO₂-enriched air through a face mask (4 minutes).

Before the final physical exercise condition, participants again relaxed in the waiting room for 15 minutes. After they had returned to the experimental room, the VU-AMS was again connected to the MS-DOS computer, and the participants were again attached to the PetCO₂ recording equipment. Next, the participants
cycled on a bicycle home-trainer, which was set at minimal resistance, while watching the computer screen. A feedback procedure was used to ensure that the same increase in heart rate was obtained (for each participant) during exercise as during mental stress. The participants were instructed to cycle faster or slower in such a way that the top of the bar on the screen was as close as possible to a set-point indicated by a line. The height of the bar represented their mean heart rate over the previous 10 seconds, and it was updated every 4 seconds. Participants were kept unaware that the height of the bar reflected their current heart rate, and that the line reflected their (previous measured and saved) mean heart rate during the corresponding part of the mental stress task. The participants’ body posture during this bicycle task was fairly similar to their posture during the mental stress and relaxation tasks. The physical exercise task was classified as successful when the differences (for each part) between the mean heart rate during the mental stress task and the mean heart rate during the physical exercise task was below 3 bpm. After 4 minutes, they again (additionally) had to breathe compressed room air through a face mask (4 minutes), and breathe compressed CO₂-enriched air through a face mask (4 minutes).

Finally, all equipment was disconnected and the electrodes were removed, participants were debriefed, paid, and sent home.

Compressed room air and 5% CO₂-enriched air breathing
Compressed room air and CO₂-enriched air were stored in two cylinders, which were located in an adjacent room. One cylinder contained medical air and the other a mixture of medical air and CO₂. Each cylinder had its own flow regulation as well as a moisturising device. The air flow from both cylinders was connected by a T-piece to a single silicon tube with an inner diameter of 7 mm, and a length of 4 meters, of which one meter came out in the experimental room. This end was fed into a silicon air reservoir, in turn connected (via a silicon tube of 32 mm inner diameter and a length of 50 cm) to a silicon half face mask (Dräger, Combitox Nova RA). This non-leaking mask, commonly used among fire workers, had two valves that separated incoming and exhaled airflow. The flow of both cylinders could be adjusted to create a part with room air and a part with an air mixture with 5% CO₂.

Physiological recordings
Interbeat Intervals (IBI’s), systolic time intervals, respiratory frequency, and a raw estimate of changes in respiratory depth (tidal volume) were measured with the Vrije Universiteit Ambulatory Monitoring System (VU-AMS version 4.3, TD-FPP, Vrije Universiteit, Amsterdam, The Netherlands). This device uses six Ag/AgCl electrodes to record the electrocardiogram and thoracic impedance (dZ). Details on the measurement procedure with the VU-AMS can be found in de

The PaCO$_2$ was estimated by measuring the partial pressure of CO$_2$ at the end of a normal expiration (PetCO$_2$). This was measured with the Capnogard etCO$_2$ Monitor (Novametrix, Walingford, CT, USA) and expressed in mm/Hg. A small tube was inserted in each of the participants’ nostrils. The values were automatically fed into a separate MS-DOS computer that was connected to the main system for synchronization of measuring intervals.

**Physiological data analysis**

The heart period data of each participant were analyzed in segments representing 128 seconds. An artefact pre-processing was performed on the IBI data by detecting outlier IBI values with three methods: (a) by absolute values (>1800 ms or <300 ms), (b) a moving average filter (> 3 SD deviation from the moving mean), and (c) by visual inspection. Since artefacts cannot simply be deleted because the continuity of time would be lost, spuriously short IBI’s were summed and missing beats were ‘created’ by splitting spuriously long IBI’s. The IBI mean values were computed from these corrected data. Next, uniformly spaced samples were created, and the segments were discrete Fourier transformed. Heart period power values were computed for the Low Frequency (LF) band (0.0625 - 0.125 Hz), and the High Frequency (HF) band (0.125 - 0.5 Hz). Changes in the HF power values were used to estimate changes in RSA. The power values were log$^{10}$ transformed to obtain normal distributions.

The thoracic impedance (dZ) data (sampled at 10 Hz) were band-pass filtered by a discrete wavelet transform filter with a cubic spline function as base (0.125 - 0.5 Hz). Next, the respiratory power values were computed from this filtered thoracic impedance (dZ) data by computing the variance of this filtered time series. Changes in the respiratory power values were used as a (raw) estimation of changes in respiratory depth (tidal volume). The respiratory power values were also log$^{10}$ transformed to obtain normal distributions. The mean respiratory frequency values were estimated from the band pass filtered thoracic impedance (dZ) data by counting the number of up-going zero crossings and dividing this value by the time of a segment. This procedure is comparable to the method used by de Geus and co-workers (1995) who computed the mean total respiratory cycle time as the mean interval between the initiating moments of inspiration.

The dZ/dt values (sampled at 250 Hz around each R-wave) were ensembled averaged over 60 seconds. The B-points were manually determined for each ensembled averaged segment, and the PEP values were determined by summing a fixed Q-to-R interval of 48 ms to the R-B interval time. The 1-minute ensembled averaged PEP’s were pooled over two succeeding values to obtain a value for each 2 minute period, similar to the other measures.
Chapter 4

Statistical data analysis

For each measure, 18 repeated observations were available for each participant (three conditions with three different breathing parts of 4 minutes, and two observations per part). To test for within-subject condition effects, the two repeated observations within each 4 minute part were averaged to yield nine within-subject values. Within-subject effects (condition x breathing manipulation) were tested with repeated measures MANOVA tests using Wilks’ Lambda. Follow-up paired t-tests were performed to test for specific condition and breathing effects. These follow-up tests (1) compared relaxation with stress and exercise during normal breathing (i.e., the conditions without breathing through the face mask), and (2) tested the specific effects of breathing the compressed CO₂-enriched air mixture compared to breathing compressed room air in each of the conditions. The alpha level was set at the .05 level for all statistical tests.

Finally, a path-analysis (using Lisrel V8.12a) was performed over the pooled covariance matrices that were computed for each participant over 18 repeated observations (for change scores in IBI, PEP, RSA, PetCO₂, respiratory depth, and respiratory frequency). This path-analysis tested for the relative contributions of the determinants to RSA as depicted in Figure 1. Because change scores (indicated with ‘Δ’ in Figure 1) were used, the intercepts were left out of the regression equations (see appendix), resulting in regression lines through the origin (representing the values during normal breathing in the relaxation condition). Degrees of freedom was set at 209 (in between the lower limit of 22, and the upper limit of 18*22).

Results

Table 1 shows the mean and corresponding standard deviation values of all measures for all nine conditions. Figures 2 to 8 show graphs (one for each measure) with bars that represent the mean within-subject change scores between each specific condition and the relaxation condition during normal breathing.

IBI & PEP

A significant overall condition effect was found for IBI ($F(8,13)=20.11$, $p<.001$) and PEP ($F(8,13)=4.73$, $p=.007$). Follow-up tests limited to the normal breathing parts revealed that, as compared to the relaxation condition, the mean IBI and PEP were significantly lower during mental stress ($T_{ib}(21)=10.55$, $p<.001$; $T_{pep}(21)=5.96$, $p<.001$) and during physical exercise ($T_{ib}(21)=12.26$, $p<.001$; $T_{pep}(21)=3.59$, $p=.002$). No significant difference was found between the IBI response to mental stress and the IBI response to physical exercise, testifying to the success of our experimental manipulation of heart rate. In spite of equal heart
Differential contributions to RSA

rate reactivity, the PEP response to mental stress was significantly larger than the PEP response to exercise ($T(21)=2.48$, $p=.022$). Follow-up tests for differences in air mixture revealed no significant differences for IBI and PEP responses to compressed room air and compressed CO$_2$-enriched air mixture during mental stress or exercise. However, as compared to compressed room air, the mean IBI was significantly lower for the compressed CO$_2$-enriched air mixture during relaxation ($T(21)=5.15$, $p<.001$). Thus, the PaCO$_2$ (and central respiratory drive) manipulation had some effects on heart rate, but only during relaxation.

Table 1. Mean and corresponding standard deviation values of all measures for all nine conditions.

<table>
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<tr>
<th></th>
<th>IBI</th>
<th>PEP</th>
<th>PetCO$_2$</th>
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<th>LF</th>
<th>Rdepth</th>
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Note: IBI = Inter Beat Interval (ms), PEP = Pre Ejection Period (ms), PetCO$_2$ = end-tidal partial pressure of CO$_2$ (mm/Hg), HF = log$_{10}$ of high frequency heart period variability power, LF = log$_{10}$ of low frequency heart period variability power, Rdepth = log$_{10}$ of respiratory power, R-freq = respiratory frequency (Hz).
Figures 2 to 7. Mean within-subject change scores (±SEM) between each specific condition and the relaxation condition during normal breathing for IBI, PEP, PetCO\textsubscript{2}, HF power, LF power, and Rdepth.
Differential contributions to RSA

**PetCO₂ respiratory power, and respiratory frequency**

Significant overall condition effects were found for the PetCO₂ ($F(8,13)=108.28$, $p<.001$), respiratory power ($F(8,13)=87.97$, $p<.001$), and respiratory frequency ($F(8,13)=11.98$, $p<.001$). Follow-up tests limited to the normal breathing parts revealed that the mean PetCO₂ and respiratory power were not significantly different during mental stress as compared to relaxation, but both were significantly higher during physical exercise ($T_{\text{PetCO₂}}(21)=5.68$, $p<.001$; $T_{\text{Rdepth}}(21)=3.16$, $p=.005$). Respiratory frequency, in contrast, increased above relaxation levels during exercise ($T(21)=6.21$, $p<.001$) as well as during mental stress ($T(21)=2.50$, $p=.021$), although the response to exercise was significantly larger ($T(21)=4.26$, $p<.001$). Taken together, the results for these respiratory parameters demonstrate that PaCO₂, respiratory depth, and respiratory frequency responses may vary across conditions independently of the magnitude of the heart rate response.

Follow-up tests for differences in air mixture revealed, as expected, a significantly higher mean PetCO₂ and respiratory power for the compressed CO₂-enriched air mixture as compared to compressed room air in all three conditions ($p$'s <.001). For respiratory frequency, no differential effects of breathing compressed room air or compressed CO₂-enriched air mixture were found during mental stress or exercise. However, during relaxation the mean respiratory frequency was significantly higher for the compressed CO₂-enriched air mixture ($T(21)=3.12$, $p=.005$), although the effect was due as much to a decrease in respiration rate during room air as to an increase during CO₂-enriched air. These PetCO₂ results are clearly indicative of successful manipulation of PaCO₂ (and central respiratory drive).
**HF and LF heart period variability power**

Significant overall condition effects were found for the HF ($F(8,13)=8.03$, $p=.001$) and LF ($F(8,13)=4.10$, $p=.012$) heart period variability powers. Follow-up tests limited to the normal breathing parts revealed that the mean HF and LF powers were significantly decreased during mental stress ($T_{HF}(21)=4.13$, $p<.001$; $T_{LF}(21)=3.73$, $p=.001$) and exercise ($T_{HF}(21)=6.64$, $p<.001$; $T_{LF}(21)=5.92$, $p<.001$) as compared to relaxation. For both powers, the response to exercise was larger than the response to stress ($T_{HF}(21)=4.08$, $p=.001$; $T_{LF}(21)=3.32$, $p=.003$).

Follow-up tests for differences in air mixture revealed, as expected, a significantly higher mean HF heart period variability power for the compressed CO$_2$-enriched air mixture as compared to compressed room air during relaxation ($T(21)=3.94$, $p=.001$) as well as during mental stress ($T(21)=4.40$, $p<.001$) and during exercise ($T(21)=3.30$, $p=.003$). In contrast, no significant effect of CO$_2$-enriched air breathing was found on the response of LF power during mental stress or during exercise, and lower rather than higher LF power was found during relaxation ($T(21)=2.40$, $p=.026$). These results demonstrate that mental stress and exercise reduced both HF and LF powers, but that the PaCO$_2$ manipulation selectively influenced HF power. The impact of the increased respiratory drive on RSA during CO$_2$-enriched air breathing was very large: the normal reduction in HF power observed during mental stress and exercise almost completely disappeared.

**Path analysis for all contributions to the HF heart period variability power**

Path analysis was performed to test for the relative contributions to within-subject changes in HF heart period variability power ($\Delta$RSA) due to changes in IBI and PEP, PetCO$_2$, respiratory power, and respiratory frequency. The model as depicted in Figure 1 resulted in an acceptable goodness of fit ($\chi^2(1)=0.034$, $p=.84$). The total variance in the changes in RSA explained by this model was 76%. The standardized beta-values are shown in Table 2. Note that in path analysis all beta and correlation coefficients are essentially partial correlation coefficients. For example, the contribution of $\Delta$PetCO2 to $\Delta$HF power is independent of the increase in respiratory depth caused by CO$_2$ breathing. The results of the path analysis indicate that, apart from cardiac vagal tone, changes in PetCO$_2$, respiratory power, and respiratory frequency had significant and independent contributions to changes in HF heart period variability power. Figure 9 shows a graph with mean within-subject changes in the HF heart period variability power across the various conditions, corrected for changes in (a) respiratory frequency, (b) PetCO$_2$, (c) respiratory power, and (d) all these determinants, using the beta-values of the path analysis. Changes in this corrected HF heart period variability power (Figure 9) closely correspond to changes in IBI corrected for changes in PEP, and
can be considered the most accurate estimation of within-subject changes in cardiac vagal tone.

**Table 2.** Standardized beta-values corresponding with the path-analysis depicted in Figure 1.

<table>
<thead>
<tr>
<th>symbol</th>
<th>path</th>
<th>beta-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_2$</td>
<td>$\Delta PEP \rightarrow \Delta IBI$</td>
<td>.58**</td>
</tr>
<tr>
<td>$\beta_1$</td>
<td>$\Delta IBI \rightarrow \Delta RSA$</td>
<td>.72**</td>
</tr>
<tr>
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<td>$\Delta PEP \rightarrow \Delta RSA$</td>
<td>-.23**</td>
</tr>
<tr>
<td>$\beta_3$</td>
<td>$\Delta PetCO_2 \rightarrow \Delta RSA$</td>
<td>.21**</td>
</tr>
<tr>
<td>$\beta_4$</td>
<td>$\Delta Rpower \rightarrow \Delta RSA$</td>
<td>.24**</td>
</tr>
<tr>
<td>$\beta_5$</td>
<td>$\Delta Rfreq \rightarrow \Delta RSA$</td>
<td>-.29**</td>
</tr>
<tr>
<td>$\delta_1$</td>
<td>$\Delta PetCO_2 \rightarrow \Delta Rpower$</td>
<td>.79**</td>
</tr>
<tr>
<td>$\delta_2$</td>
<td>$\Delta PetCO_2 \rightarrow \Delta Rfreq$</td>
<td>.12</td>
</tr>
</tbody>
</table>

*Note: ** $p<.01$ (2-tailed)*

**Figure 9.** Mean within-subject changes in HF corrected for changes in (a) respiratory frequency, (b) PetCO$_2$, (c) respiratory power, and (d) all these determinants.
Chapter 4

Discussion

The present study confirmed our hypothesis that changes in cardiac vagal tone, central respiratory drive, and respiratory depth and frequency each contribute to within-subject changes in RSA, measured as HF heart period variability power. Independence of the various effects on RSA was shown by path analysis in which changes in IBI, corrected for changes in PEP, were used as a proxy for central nervous system induced changes in cardiac vagal tone. This analysis showed that the reduction in RSA during mental stress and physical exercise was only in part accounted for by changes in cardiac vagal tone. Additional significant contributions were shown from changes in respiratory depth, respiratory frequency, and PetCO$_2$. The main new finding of the present study is, however, that situation-specificity in the relative contributions of these determinants to RSA exist.

The effects of changes in respiratory depth and frequency on RSA were as expected, and their direction confirms the previous literature (Hirsch & Bisschop, 1981; Eckberg, 1983; Grossman & Kollai, 1993; Kobayashi, 1998): task-induced reductions in RSA are enhanced by faster breathing but reduced by deeper breathing. Increased central respiratory drive strongly and independently affects the normal task-induced RSA reduction, which also confirms the previous literature (Al-Ani et al., 1996). Compared to relaxation, a pronounced reduction in IBI, PEP, and RSA was found during mental stress and physical exercise. However, the task-induced reduction in RSA was only observed under normal breathing conditions. It was nullified by 5% CO$_2$ enriched air breathing during mental stress, and greatly reduced by 5% CO$_2$ enriched air breathing during physical exercise. CO$_2$ effects were specific to RSA: the relative increase in RSA during 5% CO$_2$-enriched air breathing in all three conditions was not coupled to similar effects on IBI, PEP, or LF heart period variability power.

An important consequence of our findings is that correcting within-subject changes in RSA for changes in respiratory depth and frequency only may not always yield an optimal estimate of changes in cardiac vagal tone. Conditions with increased (or decreased) PaCO$_2$ (i.e., estimated in this study with PetCO$_2$; see Figure 8) can compromise RSA as an index of cardiac vagal tone. Fortunately, during mental stress and normal breathing conditions, the within-subject changes in RSA corrected for respiratory frequency largely paralleled the changes in cardiac vagal tone, although it did not produce a considerably better estimator than the uncorrected RSA. However, it is uncertain that this will apply to all stressors, particularly if they influence the PaCO$_2$ (e.g., as a result of hypo- or hyperventilation). Therefore, to use changes in RSA to index changes in cardiac vagal tone during exercise or mental/emotional stressors that might affect respiratory drive, RSA should be optimally corrected for changes in respiratory depth, respiratory frequency, and PetCO$_2$. Correcting for changes in respiratory depth, respiratory frequency, and PetCO$_2$. Correcting for changes in respiratory
Differential contributions to RSA

frequency only, as has been previously suggested (see Berntson et al., 1997), may under or overestimate the reduction in cardiac vagal tone.

As a result of our manipulation, a similar reduction in IBI was found during mental stress and physical exercise. However, this same heart rate response to physical exercise was brought about by a different mix of cardiac vagal and sympathetic reactivity. The reduction in PEP was larger during mental stress, while the reduction in HF (and LF) heart period variability power was larger during physical exercise. In line with our main findings, the differences in HF power reduction can be partially explained by different effects of exercise and stress in the central respiratory drive and ventilatory behavior. The respiratory frequency (for the normal breathing conditions) increased more during physical exercise than during mental stress, while the respiratory depth and the PetCO₂ increased only during physical exercise. However, inspection of the corrected HF power in Figure 9 shows that the contribution of cardiac vagal tone to exercise and stress truly varied across situations. This is most likely explained by a fundamental difference in the neural regulation of heart rate in these two conditions. During physical exercise, cardiac vagal tone is reduced and cardiac sympathetic tone is enhanced by a combination of a feedforward ‘central command’ and a feedback signal from the chemoreceptors in the working muscles (Rowell & O’Leary, 1990; Williamson, Nobrega, Winchester, Zim, & Mitchell, 1995; Potts & Mitchell, 1998). During stress, only the central command will be active with a relatively negligible increase in feedback from muscle activity. Since the muscle-heart reflexes largely operate through resetting of the baro-reflex (Potts, Shi, & Raven, 1993; Potts & Mitchell, 1998), their effect will be mainly parasympathetic in origin, specifically in the first minutes of exercise. Thus, it is not surprising that physical exercise, exploiting both feedforward and feedback signals, inhibited vagal tone more strongly than stress.

Although we tried to include all relevant determinants, our model (see Figure 1) did not explain the total variance in the changes in RSA. The exact sources of the remaining error variance need to be established but at least three factors can be identified a priori. Firstly, possible effects of accentuated antagonism of sympathetic and vagal activity at the sinoatrial node were set to zero in our model. Secondly, although an error variance for RSA (ε₁ in Figure 1) was modelled, we did not estimate (task-dependent) changes in DMNX vagal contribution to heart rate. Finally, using PEP as measure of the sympathetic control of heart rate when comparing exercise and stress may be flawed. During physical exercise ventricular preload increases and afterload decreases more than during mental stress (where a reverse effect may occur). This compromises PEP as an index of sympathetic beta-adrenergic influences on the heart (Sherwood et al., 1990). However, an increase in preload and a decrease in afterload should have yielded a lowered PEP value during exercise. Just the opposite was found. Unfortunately, preload and afterload are not the only factors to affect the validity of PEP. PEP measures the contractility of the left ventricle, which is dependent on both the amount of adrenergic
neurotransmitters as well as the affinity and density of the left ventricular adrenoceptors. Density of beta-receptors on lymphocytes has been shown to change rapidly in response to adrenaline infusion, exercise, and mental stress (Graafsm a et al., 1989; 1990), and the same may apply to cardiac receptors, specifically the ventricular beta-2-receptors (Muntz, Zhao, & Miller, 1994). This dynamic receptor regulation may be situation specific in that beta-receptor density may increase more strongly during exercise than mental stress (Graafsm a et al., 1987; 1990).

In spite of the problems mentioned above, the converging evidence of this study clearly demonstrates an important contribution of central respiratory drive to RSA that is, in part, independent of influences on cardiac vagal tone and respiratory depth and frequency. It also demonstrates situation-specificity in the relative contributions of these determinants to RSA. Although our results are strictly obtained from a within-subject design, it seems reasonable to expect that between-subject differences in RSA are also modified by individual differences in central respiratory drive. It has already been shown that strong individual differences exist in PetCO$_2$, and that these differences represent a stable trait that is associated with increased risk for hypertension and is accompanied by a tendency to worry and experience negative emotions (Dhokalia, Parsons, & Anderson, 1998). There is a growing literature showing individual differences in RSA to be predictive of hypertension or cardiac disease (Hayano et al., 1991; Kleiger et al. 1987; Martin et al., 1987; Saul et al., 1988; Singer et al., 1988; Julius et al., 1971; Mallani et al., 1991) and to correlate with low psychological well-being (Thayer et al., 1996; Watkins et al., 1998; Musselman et al., 1998). We suggest that refinement of RSA, by taking into account PetCO$_2$ (or another estimator of the central respiratory drive) in addition to respiratory frequency and depth, would help to improve the associations and predictions found in such studies.

**Acknowledgments**

The authors gratefully acknowledge the aid of Birgitte van Ginkel and Leontine Segers for their assistance in data collection, and the aid of Peter Molenaar for his statistical assistance.
Appendix

Equations corresponding with the path diagram depicted in Figure 1.

\( \Delta IBI = \alpha_1 \Delta VT_{ma} + \alpha_2 \Delta ST + \alpha_3 \Delta VT_{nnMD} \)

\( \Rightarrow (2) \quad \Delta IBI = \alpha_1 \Delta VT_{ma} + \alpha_2 \Delta PEP + \alpha_3 \Delta VT_{nnMD} + \epsilon_1 \)

\( \Rightarrow (3) \quad \Delta VT_{ma} = \frac{1}{\alpha_1} \Delta IBI - \frac{\alpha_2}{\alpha_1} \Delta PEP - \frac{\alpha_3}{\alpha_1} \Delta VT_{nnMD} - \frac{\epsilon_1}{\alpha_1} \)

\( \Delta RSA = \gamma_1 \Delta VT_{ma} + \gamma_2 \Delta PaCO_2 + \gamma_3 \Delta TiVol + \gamma_4 \Delta Rfreq \)

\( \Rightarrow (5) \quad \Delta RSA = \gamma_1 \Delta VT_{ma} + \gamma_2 \Delta PetCO_2 + \gamma_3 \Delta Rdepth + \gamma_4 \Delta Rfreq + \epsilon_1 \)

\( (3) \rightarrow (5) \quad \Delta RSA = \beta_1 \Delta IBI + \beta_2 \Delta PEP + \beta_3 \Delta PetCO_2 + \beta_4 \Delta Rdepth + \beta_5 \Delta Rfreq + \epsilon_1 \)

\( (6 + 7) \Delta Rdepth = \delta_1 \Delta PetCO_2 + \epsilon_1 \quad \Delta Rfreq = \delta_2 \Delta PetCO_2 + \epsilon_1 \)

\[ \begin{align*}
\beta_1 &= \frac{\gamma_1}{\alpha_1} \\
\beta_2 &= -\frac{\gamma_2}{\alpha_1} \\
\beta_3 &= \gamma_3 \\
\beta_4 &= \gamma_4 \\
\beta_5 &= \gamma_1 \\
\epsilon_1 &= -\frac{\gamma_3}{\alpha_1} + \epsilon_1 - \frac{\gamma_4}{\alpha_1} \Delta VT_{nnMD}
\end{align*} \]

Note: \( IBI = \) Interbeat Interval; \( VT = \) cardiac Vagal Tone; \( ST = \) cardiac Sympathetic Tone; \( PEP = \) Pre-Ejection Period; \( PetCO_2 = \) end-tidal partial pressure of \( CO_2\); \( Rdepth = \) Respiratory depth; \( Rfreq = \) Respiratory frequency

References


Part II

The relationship between psychological traits and physiological responses to stress
Chapter 5

A repressive coping style cannot be related to affective, facial, or physiological responses to looking at emotional pictures

Jan H. Houtveen, Simon Rietveld, Mirjam Schoutrop, Mark Spiering, & Jos F. Brosschot

Abstract

Previous studies have demonstrated increased physiological emotional responses despite relatively low self-reported affect for individuals with a repressive coping style as compared to control groups. The main question in the current study was whether such group differences could also be demonstrated by using the picture perception methodology of Lang. A second question was whether differences between these groups could be found in the habituation of physiological emotional responses. Repressors ($n=14$), ‘truly’ low anxious participants ($n=14$), and moderately high anxious participants ($n=13$) were selected with the Marlowe-Crowne Social Desirability Scale and the Taylor Manifest Anxiety Scale. Two sets of 27 pictures with alternating neutral, threatening, and sexual content were presented whilst valence and arousal ratings, skin conductance, heart rate, and facial muscle responses were measured. No straightforward group differences were found. The data only supported the view that differential habituation, and not a repressive coping style, may contribute to differential self-reported, facial, and physiological emotional responses.
Introduction

Differential self-reported emotional ratings, emotion-related facial expression, and emotion-related physiological responses have often been observed in the field of psychophysiological research on stress and emotions (e.g., Laan, Everaerd, van Bellen, & Hanewald, 1994; Lang, Levin, Miller, & Kozak, 1983; Skelton & Pennebaker, 1990). The combination of a relatively low self-reported emotional rating and a relatively high physiological response is of special relevance in this field. This type of differential response is considered typical for individuals with a repressive style of coping with emotions (Weinberger, Schwartz, & Davidson, 1979; Weinberger, 1990). Repression of emotions is considered to have potential negative clinical consequences, for example, it has been related to cardiovascular disease and immune function (Gross, 1989; Pennebaker, Hughes, & O’Heeran, 1987; Scheier & Bridges, 1995). Moreover, the concept of repression and/or non-expression of emotions may be particularly relevant in explaining slow physiological recovery, which has been suggested as a direct cause of stress-related diseases (Brosschot & Thayer, 1998).

Weinberger and co-workers (1979) used a combination of the Marlowe-Crowne Social Desirability Scale (MCSDS; Crowne & Marlowe, 1964) and the Taylor Manifest Anxiety Scale (TMAS; Taylor, 1953; see Bendig, 1956 for a short form) to differentiate repressors, ‘truly’ low anxious, and high anxious individuals. In their classic conceptualisation, individuals with high scores on the MCSDS and low scores on the TMAS were defined as repressors, while individuals with low scores on both the MCSDS and the TMAS were defined as truly low anxious. Individuals with high scores on the TMAS were defined as high anxious. Weinberger and co-workers (1979) used a phrase association task to validate their classification of repression. This test consisted of phrases regarding neutral, sexual, and aggressive topics. Their results demonstrated that repressors had slower responses to sexual and aggressive phrases as compared to truly low anxious participants, and they had higher levels of verbal disturbances and avoidance regarding emotional topics. Importantly, physiological measures (heart rate, skin conductance, and forehead electromyogram) indicated that repressors were actually more stressed as compared to truly low anxious participants, despite the fact that repressors scored low on trait anxiety. A moderately high anxious control group, which scored above the normative median on the TMAS, exhibited an intermediate level of stressful physiological response. Ever since, several studies have demonstrated increased physiological responses (despite low self-reported affect) for repressors as compared to truly low anxious and/or high anxious participants, as classified by a combination of the MCSDS and TMAS (Asendorpf & Scherer, 1983; Baumeister & Cairns, 1992; Brosschot & Janssen, 1998; Brown et al., 1996; Newton & Contrada, 1992).

However, further research may provide new insight into the complex relationships between the concomitants of an emotional state, and into the original
conceptualisation of repression. Lang (1995) proposed a motivational theory of emotions on the basis of a combination of affective valence and arousal. He argued that there are two motivational systems in the brain, an apetitive system and an aversive system, which determine the primacy of the valence dimension. The arousal dimension reflects variations in the metabolic and neural activation of both motivational systems. Lang, Greenwald, Bradley, and Hamm (1993) presented pictures to their participants that varied widely across the valence dimension (pleasant-unpleasant) and arousal dimension (excited-calm), during which facial muscle activity (zygomatic and corrugator electromyogram) and autonomic responses (heart rate and skin conductance) were measured. After each picture, the participants reported their experienced valence and arousal. A factor analysis revealed two factors: self-reported pleasure (valence), changes in heart rate, and changes in facial muscles on one factor, and self-reported arousal and changes in skin conductance on a second factor. Lang and co-workers (1993) used the same combination of the MCSDS and the short version of the TMAS. With their picture perception methodology, they did not find any differences between repressors and control groups neither on self-reported emotional ratings, nor on facial and physiological responses. However, the study of Lang and co-workers (1993) was not comparable to the study of Weinberger and co-workers (1979). For example, the selection criteria were not similar. Based on these differences in selection criteria, Lang and co-workers (1993) suggested that larger group differences could have been found when actual repressors were selected (i.e., selected from a larger population). The main question of the current study is whether these group differences may be found for actual repressors selected from a larger population.

Whether increased physiological responses (e.g., as found for repressors) are the result of increased reactivity or prolonged activation is not always clear. The picture perception methodology of Lang has the advantage that it creates the possibility of studying group differences in self-reported, facial, and physiological responses regarding both the valence and arousal dimensions. Moreover, this methodology may also be used to study group differences in generalization of habituation of the emotional responses. Generalization of habituation is defined as response extinction to repeated presentation of different stimuli (based on the classical definition of habituation as response extinction after repeated identical stimulus presentation; see Öhman, Hamm, & Hugdahl, 2000). One could speculate that physiological habituation patterns are particularly relevant for the development of stress-related disease. Reduced generalization of habituation during repeated (novel but to some extent similar) emotional stimulation might be related to slow physiological recovery (i.e., prolonged activation) after or during a stress situation. Some authors have suggested that slow recovery of the physiological response after an emotional situation may be more important for the development of stress-related disease than physiological reactivity (Brosschot & Thayer, 1998; Dienstbier, 1989; Linden, Earle, Gerin, & Christenfeld, 1997). It seems logical and adaptive that the emotional system habituates after repeated
exposure to identical or slightly different emotional stimulation, as the result of a reduction in novelty and unpredictability (Öhman et al., 2000). However, the different components of the emotional state (i.e., self-reported emotional ratings, facial responses, and physiological responses) may habituate differently over time. Hence, an important additional question of the current study is whether repressors have reduced generalization of physiological response habituation to emotional pictures.

The picture perception methodology of Lang was used in the current study to estimate group differences between repressors, a truly low anxious control group, and an additional moderately high anxious control group. Self-reported affective responses, physiological response patterns, and generalization of response habituation were measured regarding both the valence and the arousal dimensions. Neutral, threatening, and sexual conditions were selected (i.e., three types of stimulus contents), based on the study of Weinberger and co-workers (1979). Two sets of pictures were successively presented to study generalization of response habituation (based on the most-simple estimation of response habituation: by computing the difference in mean response amplitude between early and late trials; see Öhman et al., 2000).

By using this methodology, responses to looking at emotional pictures (i.e., threatening and sexual) may be compared to responses to looking at neutral pictures. It was hypothesised that repressors would show similar differences between their responses to emotional and neutral pictures as compared to the truly low anxious control group on their self-reported valence and arousal ratings. It was also hypothesized that repressors, as compared to the truly low anxious control group, would show larger differences between their responses to emotional and neutral pictures on the physiological measures of the valence factor (i.e., heart rate and facial muscles) and on the physiological measure of the arousal factor (i.e., skin conductance). It was further hypothesized that the additional, moderately high anxious control group, as compared to repressors and the truly low anxious control group, would show the largest differences between their responses to emotional and neutral pictures on self-reported valence and arousal ratings, while showing an intermediate level on the physiological measures. Regarding group differences in generalization of habituation, it was hypothesized that repressors, as compared to both control groups, would show the smallest reduction between the second set and the first set in the differences between their responses to emotional and neutral pictures on the physiological measures.
Method

Participants

General. Repressors, truly low anxious, and moderately high anxious participants were all recruited from a sample of 420 undergraduate students. The participants were invited for a study entitled 'looking at pictures' without informing them of the reason of their selection. They signed an informed consent and received course credits or Dfl 15 (§8) for participation.

Pre-selection. The pre-selection was based on the trait version of the Spielberger State-Trait Anxiety Inventory (STAI), completed by all undergraduate students two months before the experiment started (i.e., for another study). Individuals who scored below the normative median value of the STAI (n=203) received the MCSDS and TMAS by mail. These two questionnaires were used to select repressors and truly low anxious participants. Both groups were selected on a score in the lowest quartile of the TMAS (equal to or below value 4). The repressors (n=18) were selected on a score in the highest quartile of the MCSDS (equal to or above value 19), while the truly low anxious participants (n=18) were selected on a score in the lowest quartile (equal to or below value 17). Adopted from Weinberger and co-workers (1979), an additional control group of moderately high anxious participants was selected. These participants (n=18) were randomly selected from the subgroup of undergraduate students (n=217) that scored above the normative median value of the STAI. They scored above the normative median on the TMAS (above value 6) and below the normative median of the MCSDS (equal to or below value 17).

Final selection. All participants completed the MCSDS and TMAS (for a second time) immediately following the experimental procedure. Again adopted from Weinberger and co-workers (1979), final groupings were based on these scores rather than on the scores obtained from previous testing. Selection scores were similar to those used during the pre-selection. The final sample consisted of 14 repressors (7 men, 7 women), 14 truly low anxious participants (7 men, 7 women), and 13 moderately high anxious participants that, unintended, consisted of women only. Ages ranged between 18 and 40. Table 1 shows the mean and standard deviation values of age, the MCSDS, and the TMAS of the final groups.

Questionnaires

A Dutch translation of the Spielberger State-Trait Anxiety Inventory (STAI; Spielberger, Gorsuch, & Lustene, 1970; van der Ploeg, 1981) was used for the initial selection of low trait anxious participants. This questionnaire has 20 items, and the total score ranges from 20 to 80 points.

A Dutch translation of the short form of the Taylor Manifest Anxiety Scale (TMAS) was used to measure trait anxiety (Taylor, 1953; Bendig, 1956), and used
for Weinberger’s repressive coping style classification (Weinberger et al., 1979). This questionnaire has 20 items, and the total score ranges from 0 to 20 points. The TMAS correlates highly with other trait anxiety scales (Watson & Clark, 1984).

A Dutch translation of the Marlowe-Crowne Social Desirability Scale (MCSDS; Crowne & Marlowe, 1964) was used for Weinberger’s repressive coping style classification (Weinberger et al., 1979). This questionnaire has 33 items, and the total score ranges from 0 to 33 points.

Table 1. Means (and SD) of age, MCSDS, and TMAS scores.

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<tr>
<th>Stimulus selection</th>
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<tr>
<td>Three types of digitized colour pictures were used: 27 neutral, 18 threatening, and 18 sexual. The neutral and threatening pictures were selected from the International Affective Picture System (IAPS; Lang, Bradley, &amp; Cuthbert, 1995). The sexual pictures were digitized from slides used in earlier sex-research experiments (Janssen, Everaerd, Spiering, &amp; Janssen, 2000). The neutral pictures showed various kinds of emotionally neutral objects, e.g., plants, bushes, and household utensils. The threatening pictures showed angry, mutilated, or dead people. The sexual pictures showed nude female models and heterosexual couples engaged in oral or genital sexual activity. All pictures were carefully selected and digitally adjusted to match on stimulus dimensions as complexity, contrast, and luminance. Nine neutral pictures were randomly selected for the practice session. The remaining pictures were (for each category) randomly assigned to one of two (parallel) sets of 27 pictures each: nine neutral, nine threatening, and nine sexual pictures. There was one (randomized) order of picture presentation for each set.</td>
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<td>Apparatus</td>
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<td>The pictures were displayed on a 15-inch colour monitor connected to an MS-DOS computer system. This computer also controlled the experimental events, the presentation of the rating scales, and the synchronization with the measurement devices. Participants sat at a close distance (i.e., 40 cm) to the monitor. This</td>
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stimulus computer was placed in a (normally lit) sound-attenuated room. The apparatus for the physiological registrations was placed in an adjacent (dimly lit) room. A one-way screen and an intercom connected the two rooms.

Each trial started with a fixation point that was presented for 15 seconds on the middle of the screen. During this period, physiological base-rate values were measured. Then a picture was presented for 10 seconds, during which the physiological responses were measured (see below), and after which the emotional rating scales were presented on the screen. The average rating time was 5 seconds. After a picture was rated, a short waiting period was created in order to obtain a minimum duration of 30 seconds between the presentation of pictures, to allow values to return to base-rate.

The emotional experience of a picture could be rated on five-point scales for valence and arousal, based on the Self-Assessment Manikin (SAM; Bradley & Lang, 1994; Lang, 1980). Valence and arousal was graphically represented on these scales by changes in a cartoon figure (see Bradley & Lang, 1994). The SAM figures were digitized and displayed on the computer screen. A figure could be selected by entering the corresponding number on the keyboard: for valence from 1 (pleasant) to 5 (unpleasant), and for arousal from 1 (excited) to 5 (calm).

Facial electromyogram (EMG) activity was recorded with miniature Ag/AgCl surface electrodes filled with electrolyte gel and placed in pairs over the corrugator supercilii (frown muscle) and the zygomatic major (smile muscle) on the left side of the face. The electrode placement was in accordance with the guidelines of Fridlund and Cacioppo (1986), except that a separate reference electrode was used for each muscle. The EMG signals were pre-amplified (2000x), band-pass filtered (80-1000 Hz), rectified, processed through an integrator with a time constant of 25 ms, and further amplified (5-50x).

The electrocardiogram (ECG) was recorded with two Ag/AgCl surface electrodes filled with electrolyte gel and placed on the lateral sides of the chest (at the ninth rib). The ECG signal was pre-amplified and band-pass filtered (1.0-1000 Hz).

Skin conductance was recorded with two Ag/AgCl electrodes (1 cm² contact area). The electrodes were filled with 0.05 mol NaCl Unibase electrode paste (Fowles et al., 1981), and attached to the medial phalanges of the middle and index finger of the non-dominant hand. A minimal time period of 20 minutes was used as a stabilization period. An alternating current (AC) voltage source (30 Hz; ± 0.75 V) was used to measure the skin resistance, which was converted to a voltage (0.2 V/µS; linear within a skin resistance range of 5-200 kΩ). The output of the resistance-to-voltage converter was integrated with a time constant of 300 ms.

All physiological signals were sampled at 100 samples per second, by using a Keithly System 570 analogue to digital converter, and recorded by an MS-DOS computer system. A synchronization signal from the stimulus computer was also recorded by this computer system.
Chapter 5

Procedure
After general instruction, informed consent, and electrode placement, participants were seated at the computer and were asked to relax and to refrain from talking during the task. At this point, the physiological measurement devices were tested and adjusted. Participants were told that pictures differing in emotional content would be displayed on the computer screen, and that they should pay close attention to each picture during the entire time it was displayed. After a picture was presented, the participants had to rate it on both SAM dimensions by selecting the corresponding figures from the SAM pictures that appeared on the computer screen. Specific information was given to explain the SAM rating scales.

The experiment began with a practice session to familiarize the participants with the SAM rating system and the experimental procedure. Then the first experimental set was presented, which consisted of 27 pictures with neutral, threatening, and sexual content. The second experimental set was presented after a break of five minutes. This second experimental set also consisted of 27 pictures with neutral, threatening, and sexual content. The pictures were presented to all participants in the same order. After the second experimental set, the equipment was disconnected and questionnaires were completed. Finally, participants were debriefed, asked some evaluative questions, paid, and sent home.

Physiological data analysis
A baseline period of 10 seconds before picture onset (during which the fixation point was visible) was defined for all physiological signals. A viewing period of 10 seconds was defined for the presentation of each picture. Reactivity scores were computed for the two facial EMG signals by subtracting the mean EMG signal during the baseline period from the mean EMG signal during the viewing period. These reactivity scores were log¹₀ transformed to normalize the distribution. Inter Beat Interval times (IBI’s; used as measure for heart rate) were computed off-line from the ECG signals by detecting the time intervals between R-tops. The R-top detection level was visually adjusted and inspected for each specific segment. The reactivity scores were calculated by subtracting the mean IBI value during the baseline period from the mean IBI value during the viewing period. This measure (unfortunately) differs from the more refined heart rate reactivity reported in Lang and co-workers (1993); it includes both the heart rate acceleration and final deceleration in response to a picture. The skin resistance signal was calibrated and converted to a skin conductance value (in μS). The skin conductance response magnitudes were scored as the largest value (compared to the mean baseline value) from one to five seconds after picture onset (based on Lang et al., 1993). The obtained skin conductance responses were also log¹₀ transformed to normalize the distribution.
Statistical data analysis

The data for the nine pictures with neutral, nine pictures with threatening, and nine pictures with sexual content were pooled separately for each stimulus-set. Statistical analyses were performed using group (repressors, truly low anxious, moderately high anxious) as a between-subject factor, and picture content (neutral, threatening, sexual) and stimulus-set (first picture set, second picture set) as within-subject factors. Group differences were tested separately for the valence factor (i.e., self-reported valence, IBI, corrugator, and zygomaticus responses) and the arousal factor (i.e., self-reported arousal and skin conductance responses). Overall group differences for differential responses between neutral and emotional pictures, and overall group differences for the extinction of responses between the first and second set were tested with repeated-measures multivariate analysis of variance (MANOVA) procedures, using Wilks’ Lambda and a Bonferronni adjusted significance level of .05/2=.025. Follow-up univariate tests and univariate contrast tests were performed to test for specific picture content and stimulus-set effects, using a Bonferronni adjusted significance level of .01.

Results

Group effects

The mean self-reported and physiological responses for each group and within-subject condition are shown in Table 2. The overall repeated-measures MANOVA test for the valence factor (i.e., self-reported valence, IBI, corrugator, and zygomaticus responses) yielded no main effect for group (F(8,72)=1.10, p=.38), no interaction effect between group and picture content (F(16,62)=0.80, p=.68), no interaction effect between group and stimulus-set (F(8,70)=0.62, p=.76), and no interaction effect between group, picture content, and stimulus-set (F(16,62)=1.54, p=.12). Additionally, including gender as a covariate or performing multiple univariate tests for each of the valence factor measures yielded no main effects for group and no interaction effects with group.

A trend, however, was found for an interaction effect between group, picture content, and stimulus-set for corrugator responses (F(4,76)=3.13, p=.019). Post-hoc tests indicated that this trend (for a group difference) was limited to the threatening pictures during the first stimulus set (F(2,38)=3.14, p<.05) A Tukey HSD procedure yielded that the corrugator responses were smaller for the repressor group as compared to the moderately high anxious group (p<.05). However, this trend disappeared completely when gender was included as a covariate.
Table 2. Means (and SD) of self-reported valence and arousal ratings, Skin Conductance Level (SCL) responses [log\(^{10}\)(SCL+1)\(\mu\)S], Inter Beat Interval (IBI) responses [ms], corrugator [log\(^{10}\)(cor+1)] and zygomaticus [log\(^{10}\)(zyg+1)] responses.

<table>
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<tr>
<th></th>
<th>Repressors (n=14)</th>
<th>Truly low anxious (n=14)</th>
<th>Moderately high anxious (n=13)</th>
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<td>(M)</td>
<td>(SD)</td>
<td>(M)</td>
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<tr>
<td>sexual</td>
<td>1.25</td>
<td>0.36</td>
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</table>
The overall repeated-measures MANOVA test for the arousal factor (i.e., self-reported arousal and skin conductance responses) yielded no main effect for group ($F(4,74)=0.47$, $p=.76$), no interaction effect between group and picture content ($F(8,70)=0.68$, $p=.71$), no interaction effect between group and stimulus-set ($F(4,74)=1.04$, $p=.39$), and no interaction effect between group, picture content, and stimulus-set ($F(8,70)=0.15$, $p=.98$). Additionally, including gender as a covariate or performing univariate tests for each of the arousal factor measures yielded no main effects for group and no interaction effects with group.

Thus, the expected group differences were not found in the differences between responses to looking at neutral and emotional pictures. The expected group differences were also not found in the extinction of responses to looking at pictures between the first and the second stimulus-set presentation. The expected group differences were not found on the valence factor and they were not found on the arousal factor.

**Picture content and stimulus-set effects**

Graphs depicting the self-reported responses for each within-subject condition are shown in Figures 1 and 2. Graphs depicting the physiological responses for each within-subject condition are shown in Figures 3 to 6.

![Figures 1 and 2. Self-reported mean (± SEM) valence and arousal ratings to the neutral, threatening, and sexual pictures, for both stimulus sets.](image)

The overall repeated-measures MANOVA tests for the valence and arousal factors both yielded a significant effect of picture content ($F_{\text{valence}}(8,31)=46.79$, $p<.001$; $F_{\text{arousal}}(4,35)=60.72$, $p<.001$), and a significant effect of stimulus-set ($F_{\text{valence}}(4,35)=6.21$, $p<.001$; $F_{\text{arousal}}(2,37)=21.47$, $p<.001$). A significant interaction
effect between picture content and stimulus-set was only found for the arousal factor ($F(4,35)=6.45, p<.001$).

Figures 3 to 6. Mean (± SEM) Skin Conductance Level (SCL), Inter Beat Interval (IBI), corrugator, and zygomaticus responses to the neutral, threatening, and sexual pictures, for both stimulus sets.

Post-hoc univariate tests for picture content yielded significant effects for self-reported valence ($F(2,39)=128.66, p<.001$), self-reported arousal ($F(2,39)=59.27, p<.001$), skin conductance responses ($F(2,39)=33.29, p<.001$), IBI responses ($F(2,39)=128.66, p<.001$), corrugator responses ($F(2,39)=12.05, p<.001$), and zygomaticus responses ($F(2,39)=6.13, p<.01$). The threatening pictures were rated as more unpleasant than the neutral pictures ($F(1,40)=260.19, p<.001$), while both the threatening pictures ($F(1,40)=101.81, p<.001$) and the sexual pictures ($F(1,40)=291.25, p<.001$) were rated as more arousing than the neutral pictures. Additionally, the threatening pictures were rated as more unpleasant ($F(1,40)=167.32, p<.001$) and more arousing ($F(1,40)=7.68, p<.01$) than the sexual pictures. The skin conductance and IBI responses were larger for threatening pictures ($F_{\text{skin-con}}(1,40)=31.14, p<.001$; $F_{\text{IBI}}(1,40)=37.10, p<.001$) and sexual pictures ($F_{\text{skin-con}}(1,40)=61.33, p<.001$; $F_{\text{IBI}}(1,40)=35.96, p<.001$) than for neutral pictures, while skin conductance responses were larger for sexual pictures.
than for the threatening pictures ($F(1,40)=7.74, p<.01$). Finally, corrugator responses were larger only for threatening pictures than for neutral pictures ($F(1,40)=24.60, p<.001$) and sexual pictures ($F(1,40)=16.16, p<.001$), while zygomaticus responses were smaller for both threatening pictures ($F(1,40)=4.12, p<.05$) and sexual pictures ($F(1,40)=10.34, p<.001$) than for neutral pictures. Thus, differences between responses to looking at neutral and emotional pictures were found for all measures.

Post-hoc univariate tests for stimulus-set yielded a significant effect for self-reported valence ($F(1,40)=11.66, p<.001$). Pictures of the second stimulus-set were rated as more unpleasant than pictures of the first stimulus set. A trend was, however, found for reduced self-reported arousal ratings for pictures of the second stimulus-set ($F(1,40)=3.87, p=.06$). Further, significant stimulus-set effects were found for skin conductance ($F(1,40)=40.84, p<.001$) and IBI ($F(1,40)=8.34, p<.01$). Reduced skin conductance responses were found for pictures of the second stimulus-set, but the IBI responses (i.e., heart rate deceleration in response to a picture) were larger. Finally, a trend was found for reduced zygomaticus responses for pictures of the second stimulus-set ($F(1,40)=4.88, p=.033$). Thus, an extinction of responses during the second stimulus-set presentation was found for some of the measures. It is remarkable that although reduced arousal ratings, skin conductance, and zygomaticus responses were found for pictures of the second stimulus-set, these pictures were rated as more unpleasant.

Finally, post-hoc univariate tests for the picture content by stimulus-set interaction yielded a significant effect for skin conductance ($F(2,39)=13.71, p<.001$). The difference between skin conductance responses for both threatening and sexual pictures versus neutral pictures was larger for pictures of the first stimulus-set than for pictures of the second stimulus set ($F_{\text{threat}}(1,40)=8.16, p<.01$; $F_{\text{sexual}}(1,40)=828.13, p<.001$).

**Discussion**

No differences could be found (for both the valence and arousal factors) between participants classified as repressors, truly low anxious, and moderately high anxious, in their self-reported emotional ratings or physiological responses to emotional pictures. The hypotheses that repressors would show scores similar to those of the truly low anxious control group on self-reported emotional ratings but with larger physiological responses, while the additional moderately high anxious control group would show larger self-reported emotional ratings but with intermediate physiological responses were not confirmed. The hypothesis that repressors would show the smallest reduction of physiological responses to emotional pictures of the second set was also not confirmed. The hypothesized group differences were absent despite substantial (content specific) responses for
both the valence and arousal factors to the threatening and sexual pictures as compared to the neutral pictures. Furthermore, the hypothesized group differences in habituation were also absent despite substantial generalization of physiological response habituation to the threatening and sexual pictures as compared to the neutral pictures. Thus, whereas the manipulations of the current study were successful, the results do not support the classic concept of a repressive coping style (with repressors defined by using a combination of the MCSDS and TMAS).

Importantly, as Figures 1 to 6 show, a pronounced generalization of habituation was only selectively found for some measures. Regarding the arousal factor, a pronounced generalization of habituation was found for skin conductance response, while this was hardly found for self-reported arousal ratings. Regarding the valence factor, only the zygomaticus (smile muscle) response showed some generalization of habituation. The self-reported unpleasantness was even increased for the second stimulus-set. Although recovery of responses have been reported before when the stimulus is reintroduced after a resting interval (see Öhman et al., 2000), one could only speculate about the reason for this (selective) unexpected sensitization of self-reported valence ratings. It cannot be excluded that stimulus-set effects might have been the result of differences in the emotional content between the pictures of both sets. In that case, generalization of response habituation and differences in the emotional contents of the sets would have been confounded. However, this appears to be unlikely since: a) highly equivalent pictures (for each category) were randomly assigned to one of the two sets; and b) while generalization of response habituation was hardly found for self-reported emotional ratings, a pronounced generalization of response habituation was found for skin conductance.

Repressors appeared to have less corrugator (frowning) responses for the threatening pictures of the first stimulus-set as compared to the moderately high anxious group. However, because this difference disappeared after including gender as a covariate, combined with the fact that the moderately high anxious group consisted of women only, we must attribute this result to larger corrugator responses for women as compared to men (see also Lang et al., 1993). Thus, although deficits in spontaneous displays of negative affect have been reported in the literature for internalizers (Jones, 1935) and alexithymics (McDonald & Prkachin, 1990), the results of the current study only demonstrated differences between the sexes.

The repressors and truly low anxious participants of the current study consisted of men and women. Comparing balanced groups of men and women seems acceptable since the expected differences between repressors and truly low anxious participants have been demonstrated for men (Asendorpf & Scherer, 1983; Weinberger et al., 1979), women (Newton & Contrada, 1992), and men and women (Brown et al., 1996). Thus, the inclusion of both men and women (in balanced groups) cannot explain why the expected differences between repressors and truly low anxious participants were not found in the current study.
Additionally, including gender as a covariate did not result in significant group differences.

We compared the absolute scores on the MCSDS and TMAS used for the selection of our groups (see Table 1) with the absolute scores used in other studies that have demonstrated differences between repressors and control groups. It was found that our criteria for the selection of repressors and control groups were not different from the criteria proposed and used by these other studies (cf., Brown et al., 1996; Newton & Contrada, 1992; Weinberger et al., 1979). This implies that our selection criteria cannot explain why repression effects were not found in the current study. Lang and co-workers (1993) suggested that including extreme repressor and control groups could possibly have resulted in more differences when they are compared with the picture perception methodology. The results of the current study do not support this view.

Weinberger and co-workers (1979) emphasized that individuals with a repressive coping style were particularly threatened by the phrase association task during phrases with negative emotional content. This conclusion was based on their study, as well as on literature regarding the relationship between verbal disturbance during phrase association and the appearance of affective imagery on the Rorschach test. However, the picture perception methodology of Lang (Lang et al., 1993,1995) is not similar to the phrase association task, although the physiological responses were found to be similar. A phrase association task is an active task, while perception of pictures is passive. Thus, although it seems unlikely, we cannot exclude the possibility that relatively high physiological responses despite relatively low self-reported emotional ratings for repressors (as found by Weinberger et al., 1979) is task-specific, and cannot be generalized to looking at threatening and/or sexual pictures. Several authors argued that specifically threat to the self (or self-esteem) would trigger discordance responses in repressors (Brosschot & Janssen, 1998; Weinberger, 1990). With respect to the current data, this would imply that the expected group effects might not have been found because participants did not experience real threat to the self by looking at the emotional pictures.

Lang and co-workers (1993) averaged the heart rate responses to their pictures over the highest peaks found during the initial acceleration interval. They found that these peaks in heart rate acceleration were lower when self-reported pleasure ratings were lower. The heart rate analysis technique used in the current study was (unfortunately) less refined since the heart rate measurement interval during picture presentation was longer and included the acceleration and the deceleration responses. As a result of our longer intervals, we always found a heart rate deceleration in response to a picture. However, this deceleration was more pronounced for threatening and sexual pictures as compared to neutral pictures, and this deceleration was larger during the second picture-set. Heart rate deceleration versus acceleration in response to pictures is discussed in great details in Öhman and co-workers (2000). Such responses may be interpreted in terms of:
(a) Lang’s defense cascade model as a tendency towards freezing versus overt action; (b) Lacey’s hypothesis as an indicator of cortical processing; or (c) Obrist’s cardiac-somatic coupling hypothesis.

Highly unpleasant self-reported valence ratings and high arousal ratings combined with relatively high skin conductance responses corresponded with the threatening pictures in the first stimulus-set. However, relatively higher unpleasant self-reported valence ratings and only slightly reduced arousal ratings combined with relatively lower skin conductance responses corresponded with the threatening pictures in the second stimulus-set. Furthermore, the self-reported arousal ratings and unpleasant valence ratings were lower during the sexual pictures as compared to the threatening pictures, while the skin conductance responses were higher during the sexual pictures. Thus, a relatively low self-reported unpleasant valence and a relatively low self-reported arousal combined with a relatively high physiological activation is not a state that is specific for repressors.

The results of the current study indicate that a repressive coping style (as classified by a combination of the MCSDS and TMAS) cannot be related to reduced self-reported emotional ratings in combination with increased physiological responses to looking at emotional pictures. It can also not be related to a reduced generalization of physiological response habituation after repeated emotional picture presentation. The data only support the view that differential generalization of response habituation may contribute to differential self-reported, facial, and physiological emotional responses.

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References


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Chapter 6

Functional somatic symptoms suggestive of hyperventilation are not associated with impaired cardiorespiratory coupling

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Abstract

This study tested whether participants with functional somatic symptoms are characterized by impaired cardiorespiratory coupling. Out of 499 young, somatically healthy, female participants, the 18 women with most recent functional somatic symptoms and the 18 women with least recent functional somatic symptoms were submitted to conditions of mental stress, mild physical exercise, and relaxation during three different breathing conditions: normal breathing, breathing compressed normal air, and breathing compressed 5% CO$_2$-enriched air. Throughout, respiratory sinus arrhythmia (RSA) was measured as the high frequency heart period variability power, respiratory rate and depth were assessed by impedance cardiography, and central respiratory drive by end-tidal partial pressure of CO$_2$. Participants with functional somatic symptoms reported more base-rate tenseness, anxiety, and somatic symptoms, and these group differences increased in response to mental stress and during 5% CO$_2$ inhalation. However, no group differences were found in base-rate RSA, in the RSA-response to mental stress or physical exercise, and during 5% CO$_2$ inhalation. Also, no group differences were found in other respiratory-related physiological measures. It was concluded that functional somatic symptoms suggestive of hyperventilation are not associated with a disruption in the RSA regulatory system.
Introduction

Individuals with numerous functional somatic symptoms, that can not be explained by somatic disorders, have been frequently described in scientific literature (e.g., Da Costa, 1871; Costa & McCrae, 1985; Watson & Pennebaker, 1989; Wesseley, Nimnuan, & Sharpe, 1999). Although differences in ventilatory activity can not be completely ruled out as explanatory mechanisms for some functional somatic symptoms in some individuals (Sharpe & Bass, 1992; Troosters et al., 1999; Wientjes & Grossman, 1994), the concept of hyperventilation can generally be rejected as a causal mechanism of functional somatic symptoms (Hornsveld, Garssen, Fiedeldij Dop, van Spiegel, & Haes, 1996; Troosters et al., 1999; Wientjes & Grossman, 1994). Ambulatory transcutaneous monitoring of the partial pressure of CO₂ in individuals that were suspected to suffer from hyperventilation, demonstrated that episodes with symptoms were not preceded by hyperventilation (Hornsveld et al., 1996). Episodes with symptoms were only related to hyperventilation in a minority of these individuals. However, previous studies have mainly concentrated on respiratory behavior and the regulation of the arterial partial pressure of CO₂. Possible effects of low cardiac vagal tone or dysfunctional cardiorespiratory coupling on the regulation of arterial partial pressure of O₂ have not been considered.

In an ingenious study, Hayano, Yasuma, Okada, Mukai, and Fujinami (1996) demonstrated the physiological relevance function of the phasic linkage between the heart rate and the respiratory cycle, known as the respiratory sinus arrhythmia (RSA) phenomenon. They induced respiratory-linked heartbeat fluctuations in anaesthetized dogs after elimination of endogenous autonomic activities by atrial pacing. Their results demonstrated how artificially increased RSA increased the O₂ consumption and delivery, decreased the ratio of physiological dead space to tidal volume, and decreased the fraction of intrapulmonary shunt. Vice versa, artificially decreased RSA reduced O₂ consumption and delivery. No changes were observed in respiratory rate, tidal volume, cardiac output, minute heart rate, arterial blood pressure, O₂ saturation, and CO₂ tension. Hayano and co-workers (1996) concluded that RSA benefits pulmonary gas exchange by matching perfusion to ventilation within each respiratory cycle. Other animal studies also demonstrated that the most probable function of RSA is to improve the pulmonary O₂ transfer (see Taylor, Jordan, & Coote, 1999). RSA probably works as a fine-tuning system between respiration and pulmonary O₂ transfer. Such a fine-tuning system makes sense since the mammalian brain is extremely sensitive to O₂ deprivation.

Within-subject psychophysiological studies have demonstrated that psychological stress (Allen & Crowell, 1989; Kamphuis & Frowein, 1985; Langewitz & Ruddel, 1989) usually reduces RSA, whereas increased RSA is associated with conditions of psychological relaxation (Skakibara, Takeuchi, &
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Hayano, 1994). In fact, short-term reductions in RSA are a characteristic feature of the flight-flight stress response (Berntson et al., 1994; Berntson, Cacioppo, & Quigley, 1993a, 1993b; Cacioppo, 1994). Clinical studies have demonstrated that chronically reduced RSA and/or an excess in task-related reductions in RSA are associated with anxiety (Friedman & Thayer, 1998; Thayer, Friedman, & Borkovec, 1996; Watkins, Grossman, Krishnan, & Sherwood, 1998), and depression (Carney et al., 1995; Musselman, Evans, & Nemeroff, 1998). It has also been repeatedly demonstrated that anxiety and/or psychological distress are closely tied to somatic symptom complaints (Pennebaker, 1982; Watson & Pennebaker, 1989; Wientjes & Grossman, 1994). More specifically, it has been suggested that anxiety related to experienced physiological sensations increases the amount of reported somatic symptoms (Clark, 1988; Pennebaker, 1982). One hypothesis to connect the various findings above is to suggest that psychological stress and/or anxiety cause reduced RSA, and that reduced RSA causes or at least enhances functional somatic symptoms, possibly through its effects on O₂ regulation. The first purpose of the present study was to test a specific part of this hypothesis, namely whether individuals with numerous functional somatic symptoms are indeed characterized by low resting RSA and/or increased reduction of RSA during psychological stress.

Two manipulations that induce both increased somatic symptoms and anxiety in individuals with numerous functional somatic symptoms are hypocapnia (alkalosis) induced by voluntary hyperventilation (Hornsveld, Garssen, & van Speigel, 1995), and hypercapnia (acidosis) induced by inhalation of a CO₂-enriched air mixture (Van den Bergh, Stegen, & Van de Woestijne, 1997). This ties in nicely with the observation that under normal conditions, O₂ sensors account for only a small part of the chemical drive to breathe, whereas this so-called ‘central respiratory drive’ is very sensitive to small differences in the arterial partial pressure of CO₂ (Feldman & McRimmon, 1999). Therefore, although RSA helps to increase the efficiency of the pulmonary circulation and O₂ transfer, it is more likely to be under control of the arterial partial pressure of CO₂ than O₂. As a consequence, deviant RSA regulation in individuals with numerous functional somatic symptoms may become particularly evident during changes in partial pressure of CO₂. This could explain their enhanced vulnerability to experiencing complaints under such conditions, for which there is currently no available physiological explanation. The second purpose of the present study is to explore the effects of hypercapnia on the RSA regulation in individuals with numerous functional somatic symptoms. In healthy individuals, a hypercapnic state has been demonstrated to enhance RSA by enhancing the central respiratory drive (Al-Ani, Forkins, Townend, & Coote, 1996). We expect this normal increase in RSA as a result of CO₂-enriched air inhalation to be reduced or even reversed in individuals with numerous functional somatic symptoms.
Methods

Participants
Young women with numerous functional somatic symptoms ($n=18$) and young women without such symptoms ($n=18$), all without chronic disease, were recruited from a sample of 499 undergraduate students. Women were selected that scored equal or below the 20th percentile (value 9) and women were selected that scored equal or above the 80th percentile (value 26) on the hyperventilation symptom questionnaire, as used by Hornsveld and co-workers (1996), during a group test session. All participants completed this questionnaire (for a second time) during the experimental procedure, and all participants remained above (low in somatic symptoms; LSS group) versus below (high in somatic symptoms; HSS group) the normative median (value 16). The study was presented to them as an investigation of breathing patterns. The participants believed that they could win 100 Dutch guilders ($50$), although all received a similar amount of 30 Dutch guilders ($15$) after the experiment. All participants signed an informed consent. The study had been approved by the ethics committee of the department of Psychology, University of Amsterdam. None of the participants used medication excepting oral contraceptives in 25 women. The participants were instructed to refrain from eating, drinking (except for water), smoking, or physical exercise within one hour before the experiment. Technical problems resulted in the loss of physiological data from one participant.

Questionnaires
A Dutch version of the hyperventilation symptom questionnaire (HSQ) was used to select participants with numerous functional somatic symptoms and controls (see Hornsveld et al., 1996). This questionnaire has 31 items and assesses the frequency of symptoms during the past month. Ratings were made on a four-point scale (range 0-3), comprising the categories ‘did not occur’, ‘one or more times a month’, ‘one or more times a week’, and ‘daily’. The total score ranges from 0 to 93 points.

A Dutch translation of the Spielberger state-trait anxiety inventory (STAI; Spielberger, Gorsuch, & Lustene, 1970; van der Ploeg, 1981) was used to measure trait anxiety. This questionnaire has 20 items, and the total score ranges from 20 to 80 points.

Procedure
The experiment consisted of three conditions that were conducted in fixed order: (1) a mental stress task, (2) a ‘relaxation’ condition, and (3) mild physical exercise. Each of these conditions consisted of three parts of 4 minutes each, again
conducted in fixed order: (a) breathing normally, (b) breathing compressed normal air through a face mask, and (c) breathing compressed 5% CO₂-enriched air through a face mask. All experimental sessions took place between 11 AM and 4 PM, and lasted approximately 2.5 hours.

After general instructions, the recording electrodes were attached and connected to the Vrije Universiteit Ambulatory Monitoring System (VU-AMS version 4.3; see below). Next, the participants went into a waiting room for 15 minutes to relax, during which they were quietly sitting, they completed the questionnaires, and they read a popular magazine. Next, they entered the experimental room that was sound shielded and dimly lit. The Ambulatory Monitoring System was connected to an MS-DOS computer, and the participants were attached to the Pet-CO₂ recording equipment (see below). Next, participants had to rate their experienced symptoms, after which the mental stress task was started on the MS-DOS computer. Intelligence test questions were presented one by one on the middle of the screen. The maximum time for each question was 60 seconds and the elapsed time was visible on screen. The participants selected one of five multiple-choice responses (1 to 5) and pressed the corresponding key on the PC-keyboard. A simultaneously presented reaction time task consisted of random timed falling red and green coins on the left and right side of the screen. The participants were instructed to press the left button (located at the left side of the keyboard) when a green coin was falling on the left side, and to press the right button (located at the right side of the keyboard) when a green coin was falling on the right side. The computer acknowledged each response (or lack of response) with a brief auditory signal: a musical tone indicating a correct response and a low frequency buzz indicating error. The combined score on intelligence and reaction time tasks was expressed in Dutch guilders on screen. The initial amount was 100 Dutch guilders ($50), which gradually diminished as a result of the errors made. Real bank notes were placed in front of the participants before the task started, and withdrawn when lost. Two research assistants observed the participants and their performance at close distance to increase the stressfulness of the task. After 4 minutes, the task stopped and participants again rated their experienced symptoms. Next, the same task continued, but participants (additionally) had to breathe compressed normal air through a face mask (4 minutes). After 4 minutes, the task stopped again and participants (again) rated their experienced symptoms. Next, the same task continued, but participants had to breathe compressed CO₂-enriched air through a face mask (4 minutes). Finally, after participants again rated their experienced symptoms, the Pet-CO₂ recording equipment was disconnected and the participants were debriefed about the stress induction and accompanied to the waiting room.

After a new 15 minute period of quiet sitting and reading, the participants re-entered the experimental room for the 'relaxation' condition. The VU-AMS was again connected to the MS-DOS computer and the participants were again attached to the Pet-CO₂ recording equipment. This condition was not different
from the previous relaxation (i.e., the participants quietly sat reading a popular magazine), but after 4 minutes, they (additionally) had to breathe compressed normal air through a face mask (4 minutes), and they had to breathe compressed CO₂-enriched air through a face mask (4 minutes). The participants rated their experienced symptoms at the same moments as during the stress induction (i.e., before and after each 4 minutes period).

Before the final exercise condition, participants again relaxed in the waiting room for 15 minutes. After they had returned to the experimental room, the VU-AMS was again connected to the MS-DOS computer, and the participants were again attached to the Pet-CO₂ recording equipment. Next, the participants cycled on a bicycle home-trainer, which was set at minimal resistance, while watching the computer screen. A feedback procedure was used to ensure that the same increase in heart rate was obtained (for each participant) during exercise as during mental stress. The participants were instructed to cycle faster or slower in such a way that the top of the bar on the screen was as close as possible to a set-point indicated by a line. The height of the bar represented their mean heart rate over the previous 10 seconds, and it was updated every 4 seconds. Participants were kept unaware that the height of the bar reflected their current heart rate, and that the line reflected their (previous measured and saved) mean heart rate during the corresponding part of the mental stress task. The participants’ body posture during this bicycle task was fairly similar to their posture during the mental stress and relaxation tasks. After 4 minutes, they again (additionally) had to breathe compressed normal air through a face mask (4 minutes), and they had to breathe compressed CO₂-enriched air through a face mask (4 minutes). The participants rated their experienced symptoms at the same moments as during the stress induction and during relaxation (i.e., before and after each 4 minute period).

Finally, all equipment was disconnected, electrodes were removed, participants were debriefed, paid, and sent home.

Compressed normal air and 5% CO₂-enriched air breathing

Compressed normal air and CO₂-enriched air were stored in two cylinders, which were located in an adjacent room. One cylinder contained medical air and the other a mixture of medical air and CO₂. Each cylinder had its own flow regulation as well as a moisturizing device. The air flow from both cylinders was connected by a T-piece to a single silicon tube with an inner diameter of 7 mm, and a length of 4 meters, of which one meter came out in the experimental room. This end was fed into a silicon air reservoir, in turn connected (via a silicon tube of 32 mm inner diameter and a length of 50 cm) to a silicon half face mask (Dräger Combitox Nova RA). This non-leaking mask, commonly used among fire workers, had two valves that separated incoming and exhaled airflow. The flow of both cylinders could be adjusted to create a part with compressed normal air and a part with a compressed air mixture with 5% CO₂.
Functional somatic symptoms and cardiorespiratory coupling

Self-reported symptoms
The symptoms breathlessness, dizziness, nausea, heart pounding, tenseness, and anxiety were selected as symptoms that will most likely be experienced as a result of CO₂-enriched air inhalation (see Van den Bergh, et al., 1997). These symptoms were measured (repeatedly) on seven-point scales, ranging from 1 ‘not at all’ to 7 ‘very much’. The words were presented on the computer screen, and participants had to rate the degree they experienced the presented symptom (at that moment) and they had to type the corresponding number on the keyboard. The scores for breathlessness, dizziness, nausea, and heart pounding were pooled and named ‘somatic symptoms’, the scores for tenseness and anxiety were pooled and named ‘tenseness-anxiety’.

Physiological recordings
Inter Beat Intervals (IBI’s), systolic time intervals, respiratory rate, and a raw estimate of changes in respiratory depth (tidal volume) were measured with the Vrije Universiteit Ambulatory Monitoring System (VU-AMS version 4.3, TD-FPP, Vrije Universiteit, Amsterdam, The Netherlands). This device uses six Ag/AgCl electrodes to record the electrocardiogram and thoracic impedance (dZ). Details on the measurement procedure with the VU-AMS can be found in de Geus, Willemsen, Klaver, and van Doorne (1995) and Willemsen, de Geus, Klaver, van Dooren, and Carroll (1996).

The PaCO₂ was estimated by measuring the partial pressure of CO₂ in the exhaled air at the end of a normal expiration (PetCO₂). This was measured with the Capnogard etCO₂ Monitor (Novametrix, Walingford, CT, USA) and expressed in mm/Hg. A small tube was inserted in each of the participants’ nostrils. The values were automatically fed into a separate MS-DOS computer that was connected to the main system for synchronization of measuring intervals.

Physiological data analysis
The heart period data of each participant were analyzed in segments representing 128 seconds. An artifact pre-processing was performed on the IBI data by detecting outlier IBI values with three methods: (a) by absolute values (>1800 ms or <300 ms), (b) a moving average filter (> 3 SD deviation from the moving mean), and (c) by visual inspection. Since artifacts cannot simply be deleted because the continuity of time would be lost, spuriously short IBI’s were summed and missing beats were ‘created’ by splitting spuriously long IBI’s. The IBI mean values were computed from these corrected data. Next, uniformly spaced samples were created, and the segments were discrete Fourier transformed. Heart period power values were computed for the High Frequency (HF) band (0.125 - 0.5 Hz). Changes in these HF power values were used to estimate changes in RSA. The power values were log¹⁰ transformed to obtain normal distributions.
The thoracic impedance (dZ) data (sampled at 10 Hz) were band-pass filtered by a discrete wavelet transform filter with a cubic spline function as base (0.125 - 0.5 Hz). Next, the respiratory power values were computed from this filtered thoracic impedance (dZ) data by computing the variance of this filtered time series. Changes in the respiratory power values were used as a (raw) estimation of changes in respiratory depth (tidal volume). The respiratory power values were also log\(^10\) transformed to obtain normal distributions. The mean respiratory rate values were estimated from the band pass filtered thoracic impedance (dZ) data by counting the number of up-going zero crossings and dividing this value by the time of a segment. This procedure is comparable to the method used by de Geus and co-workers (1995) who computed the mean total respiratory cycle time as the mean interval between the initiating moments of inspiration.

The dZ/dt values (sampled at 250 Hz around each R-wave) were ensemble averaged over 60 seconds. The B-points were manually determined for each ensemble averaged segment, and the PEP values were determined by summing a fixed Q-to-R interval of 48 ms to the R-B interval time. The 1 minute ensemble averaged PEP’s were pooled over two succeeding values to obtain a value for each 2 minute period, similar to the other measures.

Statistical data analysis

For each measure, nine repeated observations were available for each participant (three conditions with three different breathing parts of 4 minutes). Base-rate differences between the groups were tested for the relaxation condition during normal breathing (i.e., the conditions without breathing through the face mask). Next, within-subject effects of condition and breathing manipulation and interactions with group were tested with repeated measures MANOVA tests using Wilks’ Lambda. The alpha level was set at the .05 level for all statistical tests.

Results

Participants

No significant group differences were found for age, length, and weight (see Table 1), smoking behavior (χ\(^2\)(1)=0.44, p=.50), sporting behavior (χ\(^2\)(1)=1.08, p=.30), and the use of oral contraceptives (χ\(^2\)(1)=0.13, p=.72). However, participants of the HSS group scored (as expected) significantly higher on the HSQ (T(34)=10.65, p<.001), but they also scored significantly higher on the STAI (T(34)=6.91, p<.001). A significant and high correlation was found between the HSQ and STAI scores (r=.86, n=36, p<.001).
Table 1. Group mean (and SD) values for age, length, weight, HSQ and STAI scores.

<table>
<thead>
<tr>
<th></th>
<th>LSS</th>
<th>HSS</th>
<th>sign.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>20.61 (2.43)</td>
<td>19.78 (1.22)</td>
<td>NS</td>
</tr>
<tr>
<td>Length</td>
<td>170.50 (6.48)</td>
<td>174.17 (6.11)</td>
<td>NS</td>
</tr>
<tr>
<td>Weight</td>
<td>63.50 (6.93)</td>
<td>64.78 (8.54)</td>
<td>NS</td>
</tr>
<tr>
<td>HSQ</td>
<td>7.61 (4.15)</td>
<td>33.28 (9.35)</td>
<td>***</td>
</tr>
<tr>
<td>STAI</td>
<td>31.17 (5.06)</td>
<td>48.94 (9.68)</td>
<td>***</td>
</tr>
</tbody>
</table>

Notes: LSS=low in somatic symptoms; HSS=high in somatic symptoms
*** p<.001 (2-tailed)

Self-reported symptoms

See Table 2 for mean values of self-reported base-rate scores (i.e., for the relaxation condition during normal breathing) and mean values of within-subject change scores with these base-rate values.

Condition and breathing manipulation. A significant condition effect was found for somatic symptoms (F(2,33)=40.22, p<.001) and tenseness-anxiety (F(2,33)=31.73, p<.001). Follow-up tests revealed significantly increased somatic symptoms and tenseness-anxiety during mental stress as compared to relaxation (F_{som-sym}(1,34)=77.35, p<.001; F_{ten-anx}(1,34)=64.83, p<.001), increased somatic symptoms during exercise as compared to relaxation (F(1,34)=17.43, p<.001), and increased somatic symptoms and tenseness-anxiety during mental stress as compared to exercise (F_{som-sym}(1,34)=18.17, p<.001; F_{ten-anx}(1,34)=54.47, p<.001). A significant breathing manipulation effect was found for somatic symptoms (F(2,33)=50.05, p<.001) and tenseness-anxiety (F(2,33)=17.72, p<.001). Follow-up tests revealed significantly increased somatic symptoms during compressed normal air breathing as compared to normal breathing (F(1,34)=21.25, p<.001), increased somatic symptoms and tenseness-anxiety during compressed 5% CO₂-enriched air breathing as compared to normal breathing (F_{som-sym}(1,34)=103.04, p<.001; F_{ten-anx}(1,34)=35.25, p<.001), and increased somatic symptoms and tenseness-anxiety during compressed 5% CO₂-enriched air breathing as compared to compressed normal air breathing (F_{som-sym}(1,34)=86.42, p<.001; F_{ten-anx}(1,34)=35.17, p<.001).

Group differences. The HSS participants reported, as expected, significantly more base-rate somatic symptoms (T(17.45)=3.08, p<.01) and tenseness-anxiety (T(18.24)=2.88, p<.01). A significant condition by group interaction was found for somatic symptoms (F(2,33)=4.92, p<.05) and tenseness-anxiety (F(2,33)=3.49,
Follow-up tests revealed that the HSS participants reported significantly more somatic symptoms and tenseness-anxiety than LSS participants during mental stress as compared to relaxation ($F_{sym}(1,34)=10.11, p<.01$; $F_{ten-anx}(1,34)=7.12, p<.01$), and they reported significantly more somatic symptoms and tenseness-anxiety during mental stress as compared to exercise ($F_{sym}(1,34)=4.19, p<.05$; $F_{ten-anx}(1,34)=5.98, p<.05$). A significant breathing manipulation by group interaction was found for somatic symptoms ($F(2,33)=5.89, p<.01$). Follow-up tests revealed that HSS participants reported significantly more somatic symptoms than LSS participants during compressed normal air breathing as compared to normal breathing ($F(1,34)=8.27, p<.01$), they reported more somatic symptoms during compressed 5% CO$_2$-enriched air breathing as compared to normal breathing ($F(1,34)=9.67, p<.01$), and they reported more somatic symptoms during compressed 5% CO$_2$-enriched air breathing as compared to compressed normal air breathing ($F(1,34)=4.53, p<.05$).

Table 2. Group mean (and SD) values for self-reported base-rate values and within-subject change scores with these base-rate values.

<table>
<thead>
<tr>
<th></th>
<th>LSS M (SD)</th>
<th>HSS M (SD)</th>
<th>sign.</th>
<th>LSS M (SD)</th>
<th>HSS M (SD)</th>
<th>sign.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>somatic symptoms</td>
<td>tension-anxiety</td>
<td></td>
<td>somatic symptoms</td>
<td>tension-anxiety</td>
<td></td>
</tr>
<tr>
<td>base-rate</td>
<td>1.03 (0.00)</td>
<td>1.54 (0.92)</td>
<td>**</td>
<td>1.08 (0.19)</td>
<td>1.78 (1.00)</td>
<td>**</td>
</tr>
<tr>
<td>stress no mask</td>
<td>0.40 (0.43)</td>
<td>1.17 (0.83)</td>
<td>**</td>
<td>1.06 (1.00)</td>
<td>2.22 (1.71)</td>
<td>*</td>
</tr>
<tr>
<td>stress normal air</td>
<td>0.39 (0.43)</td>
<td>1.28 (0.97)</td>
<td>**</td>
<td>1.02 (0.78)</td>
<td>2.33 (1.69)</td>
<td>**</td>
</tr>
<tr>
<td>stress 5% CO$_2$</td>
<td>1.28 (0.95)</td>
<td>2.50 (1.23)</td>
<td>**</td>
<td>1.44 (1.01)</td>
<td>2.92 (1.71)</td>
<td>**</td>
</tr>
<tr>
<td>relaxation normal air</td>
<td>0.06 (0.16)</td>
<td>0.54 (0.71)</td>
<td>*</td>
<td>-0.03 (0.12)</td>
<td>0.19 (0.62)</td>
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</tr>
<tr>
<td>relaxation 5% CO$_2$</td>
<td>0.65 (0.65)</td>
<td>1.50 (1.02)</td>
<td>**</td>
<td>0.36 (0.51)</td>
<td>0.92 (1.05)</td>
<td>*</td>
</tr>
<tr>
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<td>0.08 (0.19)</td>
<td>0.26 (0.74)</td>
<td>NS</td>
<td>-0.06 (0.16)</td>
<td>-0.03 (0.72)</td>
<td>NS</td>
</tr>
<tr>
<td>exercise normal air</td>
<td>0.31 (0.45)</td>
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<td>NS</td>
<td>0.00 (0.24)</td>
<td>0.14 (0.66)</td>
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<tr>
<td>exercise 5% CO$_2$</td>
<td>1.04 (0.83)</td>
<td>2.11 (1.18)</td>
<td>**</td>
<td>0.42 (0.62)</td>
<td>1.06 (1.04)</td>
<td>*</td>
</tr>
</tbody>
</table>

Notes: LSS=low in somatic symptoms; HSS=high in somatic symptoms

*p<.05  **p<.01  (2-tailed)

a) the relaxation, no mask condition is used as base-rate.
Table 3. Group mean (and SD) values for physiological base-rate values and within-subject change scores with these base-rate values.

<table>
<thead>
<tr>
<th></th>
<th>LSS M (SD)</th>
<th>HSS M (SD)</th>
<th>sign.</th>
<th>LSS M (SD)</th>
<th>HSS M (SD)</th>
<th>sign.</th>
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<tr>
<td><strong>log^10 HF power</strong></td>
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<td>base-rate(^a)</td>
<td>3.23 (0.39)</td>
<td>3.32 (0.34)</td>
<td>NS</td>
<td>0.25 (0.04)</td>
<td>0.24 (0.04)</td>
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<td>-0.33 (0.33)</td>
<td>-0.41 (0.26)</td>
<td>NS</td>
<td>0.03 (0.07)</td>
<td>0.04 (0.08)</td>
<td>NS</td>
</tr>
<tr>
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<td>-0.35 (0.27)</td>
<td>NS</td>
<td>0.02 (0.06)</td>
<td>0.03 (0.05)</td>
<td>NS</td>
</tr>
<tr>
<td>stress 5% CO(_2)</td>
<td>0.02 (0.32)</td>
<td>-0.16 (0.42)</td>
<td>NS</td>
<td>0.03 (0.05)</td>
<td>0.05 (0.06)</td>
<td>NS</td>
</tr>
<tr>
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<td>0.04 (0.26)</td>
<td>NS</td>
<td>-0.00 (0.03)</td>
<td>-0.01 (0.03)</td>
<td>NS</td>
</tr>
<tr>
<td>relaxation 5% CO(_2)</td>
<td>0.25 (0.26)</td>
<td>0.23 (0.27)</td>
<td>NS</td>
<td>0.02 (0.05)</td>
<td>0.03 (0.04)</td>
<td>NS</td>
</tr>
<tr>
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<td>-0.73 (0.38)</td>
<td>NS</td>
<td>0.08 (0.06)</td>
<td>0.07 (0.04)</td>
<td>NS</td>
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<tr>
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<td>-0.52 (0.37)</td>
<td>NS</td>
<td>0.04 (0.05)</td>
<td>0.04 (0.05)</td>
<td>NS</td>
</tr>
<tr>
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<td>-0.43 (0.46)</td>
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<tr>
<td>IBI (sec)</td>
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<tr>
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<td>0.91 (0.15)</td>
<td>0.92 (0.11)</td>
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<td>0.62 (0.27)</td>
<td>0.52 (0.28)</td>
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<td>-0.19 (0.11)</td>
<td>NS</td>
<td>0.13 (0.32)</td>
<td>0.19 (0.28)</td>
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<tr>
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<td>-0.19 (0.11)</td>
<td>NS</td>
<td>0.21 (0.34)</td>
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<td>-0.20 (0.12)</td>
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<td>0.64 (0.33)</td>
<td>0.63 (0.33)</td>
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<tr>
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<td>-0.02 (0.04)</td>
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<td>-0.20 (0.10)</td>
<td>NS</td>
<td>0.18 (0.25)</td>
<td>0.24 (0.19)</td>
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<tr>
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<td>-0.22 (0.10)</td>
<td>NS</td>
<td>0.48 (0.31)</td>
<td>0.42 (0.21)</td>
<td>NS</td>
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<tr>
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<td>-0.23 (0.08)</td>
<td>-0.24 (0.11)</td>
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<td>0.87 (0.35)</td>
<td>0.80 (0.25)</td>
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<td><strong>PEP (ms)</strong></td>
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<td></td>
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</tr>
<tr>
<td>base-rate(^a)</td>
<td>91.20 (9.03)</td>
<td>87.06 (4.67)</td>
<td>NS</td>
<td>36.90 (2.38)</td>
<td>36.47 (1.93)</td>
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<td>-2.96 (2.51)*</td>
<td></td>
<td>-0.68 (2.03)</td>
<td>-0.20 (0.96)</td>
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<tr>
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<td>-2.52 (2.95)**</td>
<td></td>
<td>0.14 (1.19)</td>
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<tr>
<td>stress 5% CO(_2)</td>
<td>-8.02 (7.22)</td>
<td>-2.78 (2.39)**</td>
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<td>7.84 (1.97)</td>
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<tr>
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<td>1.20 (2.40)</td>
<td>NS</td>
<td>0.40 (0.66)</td>
<td>0.13 (1.51)</td>
<td>NS</td>
</tr>
<tr>
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<td>-0.22 (2.41)</td>
<td>NS</td>
<td>8.06 (1.79)</td>
<td>8.46 (1.59)</td>
<td>NS</td>
</tr>
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<td></td>
<td>1.30 (0.99)</td>
<td>1.80 (1.13)</td>
<td>NS</td>
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<tr>
<td>exercise normal air</td>
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<td>-2.63 (3.56)*</td>
<td></td>
<td>3.54 (2.16)</td>
<td>3.32 (1.63)</td>
<td>NS</td>
</tr>
<tr>
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<td>-8.96 (8.02)</td>
<td>-3.35 (3.56)*</td>
<td></td>
<td>12.07 (2.41)</td>
<td>11.05 (2.45)</td>
<td>NS</td>
</tr>
</tbody>
</table>

Notes: LSS=low in somatic symptoms; HSS=high in somatic symptoms
* p<.05  ** p<.01  *** p<.001 (2-tailed)
\(^a\) the relaxation, no mask condition is used as base-rate.

Physiological measures

See Table 3 for mean values of physiological base-rate values (i.e., for the relaxation condition during normal breathing) and mean values of within-subject change scores with these base-rate values.
Condition and breathing manipulation. A significant condition effect was found for IBI \(F(2,32)=134.03, p<.001\), PEP \(F(2,32)=20.12, p<.001\), HF heart period variability power \(F(2,31)=50.02, p<.001\), respiratory rate \(F(2,31)=33.38, p<.001\), respiratory power \(F(2,31)=30.57, p<.001\), and PetCO\(_2\) \(F(2,32)=55.64, p<.001\). Follow-up tests revealed significantly reduced IBI, PEP, and HF heart period variability power values but increased respiratory rate during mental stress as compared to relaxation \(F_{\text{IBI}}(1,33)=129.04, p<.001; F_{\text{PEP}}(1,33)=40.17, p<.001; F_{\text{HFpower}}(1,33)=58.79, p<.001; F_{\text{RR}}(1,33)=10.53, p<.01\), reduced IBI, PEP, and HF heart period variability power values but increased respiratory rate, respiratory power, and PetCO\(_2\) during exercise as compared to relaxation \(F_{\text{IBI}}(1,33)=200.67, p<.001; F_{\text{PEP}}(1,33)=31.50, p<.001; F_{\text{HFpower}}(1,33)=102.82, p<.001; F_{\text{RR}}(1,33)=66.85, p<.001; F_{\text{Rpower}}(1,33)=51.16, p<.001; F_{\text{PetCO2}}(1,33)=105.77, p<.001\), and reduced IBI and HF heart period variability power values but increased respiratory rate, respiratory power, and PetCO\(_2\) during exercise as compared to mental stress \(F_{\text{IBI}}(1,33)=56.38, p<.001; F_{\text{HFpower}}(1,33)=41.06, p<.001; F_{\text{RR}}(1,33)=12.06, p<.001; F_{\text{Rpower}}(1,33)=23.46, p<.001; F_{\text{PetCO2}}(1,33)=91.07, p<.001\).

A significant breathing manipulation effect was found for IBI \(F(2,32)=13.75, p<.001\), HF heart period variability power \(F(2,31)=30.71, p<.001\), respiratory rate \(F(2,31)=12.45, p<.001\), respiratory power \(F(2,31)=173.14, p<.001\), and PetCO\(_2\) \(F(2,32)=734.37, p<.001\). Follow-up tests revealed significantly reduced IBI values and respiratory rate, but increased HF heart period variability power, respiratory power, and PetCO\(_2\) during compressed normal air breathing as compared to normal breathing \(F_{\text{IBI}}(1,33)=13.30, p<.05; F_{\text{HFpower}}(1,33)=6.01, p<.05; F_{\text{RR}}(1,33)=16.31, p<.001; F_{\text{Rpower}}(1,33)=39.06, p<.001; F_{\text{PetCO2}}(1,33)=49.44, p<.001\), reduced IBI values but increased HF heart period variability power, respiratory power, and PetCO\(_2\) during compressed 5% CO\(_2\)-enriched air breathing as compared to normal breathing \(F_{\text{IBI}}(1,33)=27.14, p<.001; F_{\text{HFpower}}(1,33)=62.64, p<.001; F_{\text{Rpower}}(1,33)=339.38, p<.001; F_{\text{PetCO2}}(1,33)=1262.53, p<.001\), and reduced IBI values and respiratory rate but increased HF heart period variability power, respiratory power, and PetCO\(_2\) during compressed 5% CO\(_2\)-enriched air breathing as compared to compressed normal air breathing \(F_{\text{IBI}}(1,33)=13.82, p<.01; F_{\text{HFpower}}(1,33)=31.53, p<.001; F_{\text{RR}}(1,33)=14.15, p<.001; F_{\text{Rpower}}(1,33)=308.36, p<.001; F_{\text{PetCO2}}(1,33)=1473.44, p<.001\).

Group differences. The groups did not differ significantly on any of the physiological base-rate values, and no interaction effects between group and breathing manipulation were found. However, one significant interaction between group and condition was found for PEP (see Figure 1; \(F(2,32)=3.82, p<.05\)). Follow-up tests revealed that HSS participants had significantly less PEP reduction than LSS participants during mental stress as compared to relaxation \(F(1,33)=7.81, p<.01\), and they had less PEP reduction during exercise as compared to relaxation \(F(1,33)=5.38, p<.05\).

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Participants with numerous functional somatic symptoms showed the expected higher base-rates in self-reported somatic symptoms and anxiety-tenseness, and these group differences sharply increased during mental stress, exercise, and during 5% CO₂-enriched air breathing. However, high levels of functional somatic symptoms were not related to reduced base-rate RSA values or to larger task-related RSA reductions. Additionally, participants with numerous functional somatic symptoms did not show relatively lower RSA-values in response to inhaling the CO₂-enriched air mixture during any of the tasks. Finally, the groups did not show differences on PetCO₂, heart rate, tidal volume, or respiratory rate. The results of the current study, therefore, clearly indicate that functional somatic symptoms suggestive of hyperventilation could not be associated with a disruption in the RSA regulatory system.

It should be noted that the participants with numerous functional somatic symptoms were not selected from a clinical population. Nonetheless, they reported high scores on the used hyperventilation symptom questionnaire, similar to the
scores of the patients measured by Hornsveld and co-workers (1996). They also reported high scores on trait anxiety, and they experienced pronounced increased somatic symptoms during the tasks and air mixture manipulations of the current study. Thus, although the results of this study do not exclude the possibility that a clinical population may show reduced RSA values (as found by Thayer et al., 1996; Watkins et al., 1998), it does demonstrate that reduced RSA values may not (generally) be related to functional somatic symptoms.

The expected relation was found between somatic symptoms and tenseness-anxiety scores. Because functional somatic symptoms are closely tied to anxiety and/or psychological distress (Watson & Pennebaker, 1989; Pennebaker, 1982; Wientjes & Grossman, 1994), a possible explanation may be found in an anxiety-related lowered threshold for detection of physical symptoms in individuals with numerous functional somatic symptoms. There is evidence that highly anxious individuals attend more to bodily symptoms, and that attention to bodily symptoms increases the perceived intensity of these symptoms (Pennebaker, 1982; Pennebaker & Skelton, 1978; Pennebaker & Lightner, 1980). Thus, the increased self-reported anxiety and tenseness of the participants with numerous functional somatic symptoms could have resulted in increased functional somatic symptoms as a result of this psychological mechanism.

A reduced PEP reactivity was found for participants with numerous functional somatic symptoms compared to the control group. This difference might indicate a difference between the groups in beta-adrenergic influence on the heart (Sherwood et al., 1990; Bum-Hee, Dimsdale, & Mills, 1999), indicating that participants with numerous functional somatic symptoms have reduced beta-adrenergic reactivity. Bum-Hee and co-workers (1999) demonstrated that tension-anxiety ratings (measured by the ‘profile of mood states’) are negatively correlated with beta-adrenergic receptor density, even in participants who do not have psychiatric illness. However, another explanation for the observed reduced PEP reactivity for participants with numerous functional somatic symptoms may be an increased tendency to respond to stress with increases in peripheral vascular resistance. Manuck, Kamarck, Kasprowicz, and Waldstein (1993) identified stable individual differences in cardiovascular reactivity in response to psychological stress caused by a mental arithmetic task. Cardiac output (i.e., the product of heart rate and stroke volume) reactors were identified based on a relatively high rise in cardiac output and relatively high PEP reactivity, while peripheral vascular resistance reactors were identified based on a relatively high rise in peripheral vascular resistance and relatively low PEP reactivity. The correlation between peripheral vascular resistance and PEP reactivity reflects an effect of an increased afterload that lengthens PEP, and may thus mask a true increase in cardiac sympathetic drive (Sherwood and co-workers, 1990). Therefore, our PEP results may not have signaled lower sympathetic reactivity for participants with functional somatic symptoms, but increased peripheral vascular resistance reactivity and/or lowered cardiac output reactivity. Since no blood pressure was
measured, this question could not be properly resolved and deserves future attention.

The results of the current study indicate that reduced RSA values are not (generally) related to functional somatic symptoms. RSA still may have its effect on the regulation of arterial partial pressure of O₂. However, the results also indicate that a dysregulation in the arterial partial pressure of O₂, as a result of a impaired cardiorespiratory coupling, can not (generally) be related to functional somatic symptoms.

Acknowledgments

The authors gratefully acknowledge the aid of Marte Kaan and Marthe de Bel for their assistance in data collection.

References


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Alexithymia: A disruption in a cortical network?
-an EEG power and coherence analysis-

Jan H. Houtveen, Bob Bermond, & Martin R. Elton

Abstract

This study was designed to test the hypothesis that alexithymia reflects reduced interaction between modules of the integrated cortical neural network responsible for emotional processing. Two groups of 10 high and low scoring subjects were formed from undergraduates using their responses on an alexithymia questionnaire in a double-blind design. The EEG was recorded continuously from homologous occipital, parietal, temporal, and frontal recording sites during the presentation of film excerpts, one of neutral and two of emotional content. For each film, the last two minutes of EEG was digitally saved for off-line power and partial multiple intra- and interhemispheric coherence analysis of the alpha and beta frequency bands. It was found that alexithymics have reduced coherence between the right frontal lobe and the left hemisphere, independent of film. Power demonstrated a significant reduction of alpha for both emotional films, which was most pronounced at the parietal leads.
Introduction

Alexithymia can be defined as a cognitive-affective disturbance characterized by difficulties in the capacity to experience and express emotions (Taylor, 1984; Krystal, 1988). Alexithymic individuals show a difficulty in identifying and describing affects, have an inability to use affects as signals of inner conflicts or of responses to external situations, have restricted imaginative processes, and they have an externally-oriented cognitive style (Taylor, Bagby, & Parker, 1989).

A neurophysiological model for alexithymia posits that it has as a contributory neurophysiological basis a deficit in the interhemispheric communication (Hoppe & Bogen, 1977; TenHouten, Walter, Hoppe, & Bogen, 1987, 1988; Zeitlin, Lane, O'Leary, & Schrift, 1989; Dewaraja & Sasaki, 1990; Bermond, 1995). The model rests on the assumptions that, in normal right-handed persons, the right hemisphere is required for emotional information processing, while the left hemisphere is required for verbal and conscious information processing. Therefore, the production of a normal affective response requires a normal interaction between the two hemispheres (Krystal, 1988; TenHouten et al., 1987, 1988; Zeitlin et al., 1989; Bermond, 1995). In their review article, Gainotti, Caltagirone, and Zoccolotti (1993) suggested a complementary role for the right and left hemispheres in emotional behaviour, with a relatively superior role for the right hemisphere in the regulation of emotional arousal and autonomic response to emotional stimuli, and a relatively superior role for the left hemisphere for both the cognitive and communicative aspects of emotions. They further postulated a magnification of the specific roles played by the right and left hemispheres in the processing and regulating of emotions at the level of the frontal lobes.

A study by Zeitlin et al. (1989) showed a deficit in interhemispheric transfer for alexithymic, neurologically-intact subjects (Vietnam veterans) on a tactile finger location task. They interpreted this impairment for alexithymics as due to a 'functional disconnection' of the two cerebral hemispheres. Dewaraja and Sasaki (1990) also found an indication for a deficit in the interhemispheric transfer for alexithymics, but specifically from the right to the left hemisphere.

In a more general model, alexithymia is considered to be a disruption in the integrated cortical neural network responsible for emotional processing. For emotional processes, a hierarchy of multiple networks is assumed that is distributed across the brainstem, limbic, paralimbic, and neocortical regions (Bear, 1991; Derryberry & Tucker, 1992; Tucker, 1993). For alexithymic individuals a dysfunction at the highest neocortical level of this hierarchy is hypothesized. Modules at this level (located mainly at the frontal neocortical regions) are essential for the highest level of emotional processing (Fuster, 1989).

Bermond (1995) distinguished two forms of alexithymia based on the presence or absence of what he defined as the emotional experience (the undifferentiated mental emotional arousal that can be experienced as a component of an emotion). Type I alexithymia is characterized by the absence of the
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emotional experience and, consequently, by the absence of the emotion accompanying cognitions. Type II alexithymia is characterized by the presence of the emotional experience and the absence of the normally accompanying cognitions. Bermond (1995) argued that particularly Type II alexithymia reflects an interhemispheric transfer deficit, and may be the result of a corpus callosum dysfunction. This thesis is based on the split brain studies of Gazzaniga and LeDoux (1978). Gazzaniga and LeDoux postulated that the cognitive components of stimuli presented to the right hemisphere reach the conscious left hemisphere directly by means of the corpus callusum, while the emotional value is first projected downwards to the limbic system and from there reaches the left hemisphere by the anterior commissure. Consequently, blocking the function of the corpus callosum can result in a specific type of alexithymia (Type II) in which the person still experiences emotional feelings, but has, beside this undifferentiated emotional arousal, no conscious cognitions concerning these emotional feelings.

The present study was designed to test the hypothesis that Type II alexithymia reflects reduced interaction between the modules of the integrated cortical neural network responsible for emotional processing in a neurologically intact population. Interhemispheric communication (between modules located in the frontal right and left cerebral hemispheres of the brain) may be impaired in Type II alexithymic individuals.

Differences between experimental conditions in the power distribution of EEG-frequencies, such as suppression of the alpha rhythm, may be used to detect a change in the subject's state of arousal or attention, and can be detected by performing a power spectral analysis (Cooper, Osselton, & Shaw, 1980). Additionally, coherence analysis may be conducted to describe the relationship between brain regions as expressed by their synchronous EEG activity. Coherence is a measure of the correlation of spectral energies between any pair of channels as a function of frequency, and is obtained by normalising the cross-spectrum of two channels by the product of their auto-power spectra (Enochson & Otnes, 1968; Dumermuth, 1977; Chatfield, 1980; Cooper et al., 1980; Gottman, 1981; Dumermuth & Molinari, 1987, 1991). Coherence may be understood as a measure of the similarity of wave shape in a given frequency band between two signals, allowing a time shift between them. This value is always between 0 and 1 and is closely analogous to the square of the correlation coefficient. The advantage of coherence analysis over power data is its dependency on the spatial properties of a neural network. Disadvantages are the dependency of the coherence values on the choice of the reference (French & Beaumont, 1984; Nunez, et al., 1994), and volume conduction that can confound the coherence values and may be misinterpreted as shared activity of brain tissue (Nunez, et al., 1994). However, although an explanation of coherence solely by spherical volume conduction would predict a spatial homogeneous distribution of EEG coherence, Thatcher, Krause, and Hrybyk (1989) demonstrated a considerable lack of homogeneity in
the spatial distribution of EEG coherence recorded from the scalp. As a result, they concluded that the contribution of various fibre systems must be considered in the formulation of any model of human EEG coherence and that, in addition to volume conduction, both local and distant coupling between cortical neural generators are reflected in coherence. It is for this reason that this measure is chosen in this study.

It is, however, controversial whether coherence between electro-physiological signals from different parts of the brain may be interpreted as dependent on a structural connectivity or as an indication of functional coupling (task dependent) between these parts (Cooper et al., 1980). Researchers have applied power and coherence analyses to detect task dependent changes within or between the hemispheres, as well as to differentiate clinical groups (Beaumont, Mayes, & Rugg, 1978; Shaw, O'Connor, & Ongley, 1978; French & Beaumont, 1984). In their review of EEG coherence studies, French and Beaumont (1984) concluded that a differentiation of clinical groups is a valid application for coherence, although the question of whether performance on a specific task leads to a general increase in coherence in comparison to a 'resting' state has not been answered conclusively. Schellberg, Besthorn, Klos, and Gasser (1990) measured the EEG power as well as the intra- and interhemispheric coherences of right-handed, male subjects while they watched emotional (positive and negative) and neutral video films. Power analysis revealed a significant decrease of alpha power for the emotional films. Coherences demonstrated no main effect for film. They, however, found an interaction between film and the coherence topography. In studies of Tucker and Dawson (1984) and Hinrichs and Machleidt (1992), emotional states were induced by recollection and imagination. In both studies, changes in alpha power and coherences were found between emotion conditions, but in different relations to each other. The vast majority of studies, reviewed in French and Beaumont (1984), demonstrated no straightforward task-related coherence effects. However, Tucker, Roth, and Bair (1986) found parallels between asymmetries in the coherence topography and anatomical asymmetries of the human cortex, and TenHouten et al. (1987,1988) found differences between corpus callosotomy patients and controls in interhemispheric alpha-band coherences while both groups watched a symbolic emotional film. Thus, although it is doubtful whether coherence varies with cognitive activity, it may be used as a measure for structural connectivity between cortical regions.

A problem in the interpretation of the interhemispheric coherences exists. This problem is based on the estimation that the majority of fibres entering the gray matter of the cortex arise from within the same hemisphere (Nunez, 1981). As a result of this, most of the variance of a specific channel (area) is accounted for by the other channels (areas) of this hemisphere. This may mask the interhemispheric coherence. In most previous coherence research, coherence has been computed between pairs of channels, usually for the alpha frequency band (see French & Beaumont, 1984). This approach results in an enormous number of coherences to
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A possible solution to these problems is factoring of the coherence matrix (Tucker & Roth, 1984). An alternative approach is the computation of the partial multiple coherences (Enochson & Ottes, 1968; Tucker et al., 1986). This approach offers the possibility to compute for each channel the intrahemispheric partial multiple coherence, representing the coherence between that channel and all other ipsilateral channels, after the variance accounted for by all contralateral electrodes has been partialled out, and to compute the interhemispheric partial multiple coherence, reflecting the coherence between that channel and all other contralateral channels, after the variance accounted for by all the other ipsilateral electrodes has been partialled out (Tucker et al., 1986). This might also reduce the contribution of volume conduction to coherence values.

In this study the power-spectra and the intra- and interhemispheric partial multiple coherences, as described in Tucker et al. (1986), are computed for the alpha and beta frequency bands. These measures are used to examine differences between alexithymic (Type II) and non-alexithymic individuals while they watch neutral and emotional video films. Insofar as EEG power and coherence measures are modulated by the emotional content of films a decrease in alpha power, independent of group, as an indication of emotional activation is hypothesized for emotional films relative to a neutral film. For reasons presented above, specifically lower frontal interhemispheric partial multiple coherences are hypothesized for the alexithymic individuals compared with controls while they watch emotional video films. No differences for the interhemispheric partial multiple coherences are hypothesized for the other leads. Since Dewaraja and Sasaki (1990) only found a right to left transfer deficit for alexithymic individuals for nonlinguistic, symbolic information (in the assumption that the right hemisphere is more specialized in symbolic information processing), the expected effect might be specific for a symbolic emotional video film compared to a blatant emotional video film.

Methods

Alexithymia assessment

Alexithymia was measured using the Bermond-Vorst-Alexithymia-Questionnaire (BVAQ), developed by the faculty of Psychology of the University of Amsterdam. The items loaded in a group of 465 first-year psychology students on five factors, which together explained 49% of the variance, producing five subscales each measuring a component of alexithymia. These subscales were interpreted as relating to the capacity to experience emotional feelings, the capacity to verbalise these experiences, the capacity to differentiate among various emotional feelings, the capacity to reflect about or analyse emotional experiences, and the capacity to fantasize about them. Each subscale consists of eight items (four positive and four negative). The internal reliability of the total scale is .89. Reliabilities for the
subscales varies between .77 and .89. By the aid of this questionnaire we were able to measure the various components of alexithymia, and to make a distinction between type I alexithymia (scoring low on all traits) and type II alexithymia (scoring high on the capacity to experience emotional feelings, but low on the other traits) as outlined in the introduction.

**Subjects**

First-year psychology students from the intake 1994 \( (n=373) \) of the University of Amsterdam were screened using the BVAQ. For four of the subscales, the population was divided in three equal parts scoring low, average, or high on that particular scale. The non-alexithymic individuals were selected by scoring high on the capacity to experience emotional feelings, high on the capacity to verbalise these experiences, high on the capacity to differentiate among various emotional feelings, and high on the capacity to fantasize about them. The alexithymic individuals (Type II) were selected by scoring high on the capacity to experience emotional feelings, but low on the other three subscales. No distinction is made based on the subscale measuring the capacity to analyse emotional experiences. Since psychology stresses the importance of analysing emotional experiences, psychology students probably don't easily indicate that they fail to do so. Likewise, it is our experience that alexithymic people who have been in psychotherapy (in which they have been taught that analysing is important) score high on this subscale while scoring low on the other subscales of the questionnaire. Subjects were further selected for right-handedness (Oldfield, 1971), absence of neurological history, and no usage of medication known to affect the EEG. The final sample consisted of 10 subjects who were considered to be highly alexithymic (1 male, 9 females; mean age = 22.6 \( SD = 2.18 \)), and 10 subjects who were considered to be non-alexithymic (2 males, 8 females; mean age = 21.6 \( SD = 1.65 \)). 16 out of 20 subjects received course credit for participating. The remaining 4 subjects were paid.

**Film stimuli**

The selection of the clips was based on an evaluation in a pilot study in the laboratory. The warming-up video clip showed a documentary about art and lasted 10 minutes. The emotionally neutral (control) film clip lasted four minutes and showed old buildings and scenery in and around a Dutch village. The original sound was replaced by quiet chamber music. The symbolic anxiety film clip showed the first eight minutes of the film 'Don't look now'. The film portrayed a child playing at the water side, while visual symbols and the music powerfully suggested frightening expectations concerning the well-being of the child. The (blatant) film clip, used to elicit fear, was composed of the first nine minutes of the film 'Cujo'. In this film a wild dog with rabies attacks a woman and her child
sitting in their car. In the last two minutes the woman cautiously leaves her car, with music creating a strong atmosphere of fear. All three experimental video clips were controlled so that no spoken words occurred during the last two minutes (EEG recording).

**Procedure**

In this double-blind experiment, subjects (unaware of the fact that they were selected on basis of their alexithymia scores) were told that the purpose of the experiment was to measure their EEG activation while they were watching the video film clips. Subjects were seated in a comfortable armchair in a dimly-lit, sound-attenuated room. First, they were shown the warming-up video. No measurements were taken during this video clip. Afterwards, the three experimental video clips were shown in randomized order so that all possible sequences of film clips occurred equally often. Prior to showing each experimental video clip, subjects were instructed that they had to write down the emotional feelings they experienced during the video after it had ended. This instruction was given to ensure that subjects attended to the film content. After the presentation of each video clip, sufficient time was given for the subjects to return to a baseline emotional state. EEG was recorded during the last two minutes of the experimental video clips. Finally, subjects completed additional questionnaires.

**Apparatus and EEG recordings**

The film segments were presented to the subjects on a 19 inch standard PAL colour video monitor at a distance of approximately two meters from the subject. A speaker for monophonic sound was located next to the monitor. EEG and EOG recordings were made using a 10 channel polygraph (Nihon Kohden 5208). The EEG was recorded from F3,F4,T3,T4,P3,P4,O1,O2 according to the international 10-20 system using tin electrodes mounted in an electrode-cap. Because a dependency of the coherence on the selection of the reference exists, and reliable coherence effects can only be found when a noncephalic reference electrode is used (French & Beaumont, 1984; Nunez et al., 1994), all the EEG derivations were referenced to the linked earlobes that were each initially buffered with operational amplifiers before they were connected. The choice of the buffered and linked earlobes (this equals averaging the earlobes) is supported by the simulation study of Rappelsberger (1989), who found reliable coherence results when reference recording was used. Nunez et al. (1994), on the contrary, found a dependency on the choice of the reference in simulation studies, even with a 'quiet' reference. However, as Rappelsberger (1989) argues, the choice of linked earlobes as reference is not compromised when, as in the present study, emphasis is directed to relative, rather than absolute, coherence values, e.g. between groups or conditions. In addition to EEG, bipolar vertical and horizontal EOG's were
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recorded, using tin electrodes, from above and below the right eye, and lateral to the outer canthus of each eye. Impedance was kept below 5KΩ for all leads. EEG's and EOG's were recorded using a 1.0 second time constant and a lowpass filter setting of 35 Hz.

Power and coherence data analysis
For each film the two minutes of EEG and EOG data were digitized (128 Hz) into 15 epochs of eight seconds (15 x 1024 samples) for each channel. Epochs with clips, drift, artefacts, or (EEG only) flat lines were discarded from further analysis. Ocular artefacts in the EEG time series were controlled by regression analysis in the time domain. The remaining time series obtained were tapered with a cosine-bell (Hanning) window for the whole epoch to correct for leakage. The mean voltage was subtracted from each data point. EEG data segments were submitted to Fast Fourier Transformation. The power and cross spectra were computed and averaged over the successive epochs for each film, and over the adjacent frequencies for the alpha (6.875-11.5 Hz) and beta (11.625-15.0 Hz) frequency bands.

For each channel, film, and frequency band the inter- and intrahemispheric partial multiple coherence were computed, as described in Tucker et al. (1986).

Statistical analysis
Power and coherences were transformed toward the normal distribution using \( \ln(x+1) \) for power, and a Fisher's Z-transformation for the two types of coherences. A repeated measure MANOVA was conducted for power, intra- and interhemispheric coherence, with alexithymia(2) as the between-group factor and frequency(2), film(3), hemisphere(2), and lead(4) as repeated measures factors (alpha=.05). As a follow-up procedure a MANOVA was conducted for each of the two frequency bands. The alpha-level for these tests was adjusted to .05/2 = .025 (Bonferroni procedure). In a follow-up procedure for the interhemispheric coherence, a MANOVA was conducted separately for each of the four leads (alpha-level set to .05/4=.0125).

Results
The emotional manipulation of the video clips was checked by content analysis of the descriptions of the subjects' emotional states which they wrote down after each video clip. A significant effect for film was found \( F(2,36)=5.50, p<.01 \) indicating an increase in the usage of emotion-related words for the two emotional video clips compared with the neutral video clip. A more detailed analysis involving
group and type of words produced was conducted, but these results are not relevant to this study.

Film
The MANOVA analysis for power yielded a significant interaction between film and lead ($F(6,13)=3.81, p<.025$), indicating a reduction in power for both emotional films at the parietal leads. This analysis also yielded a significant interaction between frequency band and film ($F(2,17)=9.75, p<.01$). Analyses for power per frequency band yielded a trend for film in the alpha frequency band ($F(2,17)=4.02, p=.037$), indicating a reduction in alpha power for both emotional films (see Figure 1). The analysis for the alpha frequency band also yielded a significant interaction between film and lead ($F(6,13)=3.72, p<.025$), indicating that the reduction in alpha power for both emotional films was more pronounced for the parietal leads.

![Figure 1](image-url)  
Figure 1. Mean alpha and beta power values for the neutral, symbolic-emotional, and blatant-emotional video clip.

The MANOVA analysis for the intrahemispheric coherence yielded a significant interaction between film and lead ($F(6,13)=6.04, p<.01$), indicating a reduction in the intrahemispheric coherence for the parietal and occipital leads for the symbolic
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anxiety film compared with the two other films (Table 1). Finally, the MANOVA analysis for the interhemispheric coherence yielded no significant film effects.

**Alexithymia**

The MANOVA analysis for the interhemispheric coherence yielded a trend for the three-way interaction between alexithymia, hemisphere, and lead ($F(3,16)=4.52$, $p=.093$). The follow-up MANOVA analyses for the interhemispheric coherence for each of the four leads yielded a significant interaction between alexithymia and hemisphere only for the frontal lead ($F(1,18)=7.80$, $p<.0125$), indicating that the non-alexithymic individuals had a higher coherence (pooled over all films) between the right frontal lead and the left hemisphere than the alexithymic individuals (see Figure 2). This interhemispheric coherence effect is specific for the frontal lead. The MANOVA analyses for power and the intrahemispheric coherences yielded no significant alexithymia effects.

**Table 1.** Grand means for the intra- and interhemispheric multiple partial coherences for each film and electrode location, averaged over the hemispheres and the two frequency bands.

<table>
<thead>
<tr>
<th>Intrahemispheric Coherence</th>
<th>O</th>
<th>P</th>
<th>T</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral film</td>
<td>.711</td>
<td>.780</td>
<td>.604</td>
<td>.471</td>
</tr>
<tr>
<td>Symbolic anxiety film</td>
<td>.689</td>
<td>.763</td>
<td>.597</td>
<td>.472</td>
</tr>
<tr>
<td>Blatannt anxiety film</td>
<td>.715</td>
<td>.777</td>
<td>.581</td>
<td>.477</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interhemispheric Coherence</th>
<th>O</th>
<th>P</th>
<th>T</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutral film</td>
<td>.679</td>
<td>.536</td>
<td>.369</td>
<td>.740</td>
</tr>
<tr>
<td>Symbolic anxiety film</td>
<td>.686</td>
<td>.554</td>
<td>.364</td>
<td>.733</td>
</tr>
<tr>
<td>Blatannt anxiety film</td>
<td>.686</td>
<td>.544</td>
<td>.353</td>
<td>.741</td>
</tr>
</tbody>
</table>

*Note: O = occipital  P = parietal  T = temporal  F = frontal*

**Frequency band**

The MANOVA analyses for power yielded a significant main effect for frequency band ($F(1,18)=53.92$, $p<.001$), indicating a lower power for the beta frequency band (Table 2). Significant lower values for the beta band were also obtained for both the intrahemispheric coherence ($F(1,18)=28.68$, $p<.001$) and for the interhemispheric coherence ($F(1,18)=131.56$, $p<.001$).
Table 2. Grand means for power and the intra- and interhemispheric multiple partial coherences, for each electrode location and the two frequency bands.

<table>
<thead>
<tr>
<th>power</th>
<th>O1</th>
<th>O2</th>
<th>P3</th>
<th>P4</th>
<th>T3</th>
<th>T4</th>
<th>F3</th>
<th>F4</th>
</tr>
</thead>
<tbody>
<tr>
<td>alpha</td>
<td>17.6</td>
<td>17.1</td>
<td>21.2</td>
<td>21.1</td>
<td>13.6</td>
<td>14.2</td>
<td>19.7</td>
<td>19.4</td>
</tr>
<tr>
<td>beta</td>
<td>13.6</td>
<td>12.8</td>
<td>14.0</td>
<td>14.4</td>
<td>11.0</td>
<td>10.9</td>
<td>12.0</td>
<td>12.0</td>
</tr>
</tbody>
</table>
| intrahemispheric coherence
| alpha          | .707 | .716 | .797 | .790 | .656 | .654 | .497 | .514 |
| beta           | .701 | .697 | .763 | .744 | .540 | .525 | .440 | .441 |
| interhemispheric coherence
| alpha          | .730 | .721 | .595 | .582 | .389 | .399 | .763 | .771 |
| beta           | .640 | .644 | .505 | .495 | .331 | .328 | .706 | .711 |

Note: O = occipital  P = parietal  T = temporal  F = frontal

Figure 2. Mean frontal left to right and frontal right to left interhemispheric multiple partial coherence values, for the non-alexithymic and alexithymic subjects.

Lead

The MANOVA analysis for power yielded a significant main effect for lead ($F(3,16)=17.68, p<.001$), indicating a decrease in power across leads in the order: parietal, frontal, occipital, temporal. The interaction between frequency band and lead was significant as well ($F(3,16)=29.39, p<.001$). Analyses for power per
frequency band yielded a significant main effect for lead in the alpha frequency band \( (F(3,16)=40.43, p<.001) \), indicating a decrease in power across leads in the order: parietal, frontal, occipital, temporal. It also yielded a significant main effect for lead in the beta frequency band \( (F(3,16)=7.23, p<.01) \), indicating a decrease in power across leads in the order: parietal, occipital, frontal, temporal.

The MANOVA analysis for the intrahemispheric coherence also yielded a significant main effect for lead \( (F(3,16)=120.46, p<.001) \), indicating a decrease in intrahemispheric coherence across leads in the order: parietal, occipital, temporal, frontal. Thus, the intrahemispheric coherence appears to vary according to the anterior-posterior location, with the highest intrahemispheric coherence for the parietal lead, and the lowest intrahemispheric coherence for the frontal lead. The interaction between frequency band and lead was significant \( (F(3,16)=26.52, p<.001) \). Analyses per frequency band yielded a significant main effect for lead in the alpha frequency band \( (F(3,16)=123.37, p<.001) \), and a significant main effect for lead in the beta frequency band \( (F(3,16)=98.07, p<.001) \), both indicating a decrease in intrahemispheric coherence following the same order of leads, but with a different slope.

Finally, the MANOVA analysis for the interhemispheric coherence yielded a significant main effect for lead \( (F(3,16)=173.83, p<.001) \), indicating a decrease in interhemispheric coherence across leads in the order: frontal, occipital, parietal, temporal. For this measure the highest values were found for the frontal lead and the lowest values for the temporal lead. The interaction between frequency band and lead was significant \( (F(3,16)=4.55, p<.025) \). Analyses per frequency band yielded a significant main effect for lead in the alpha frequency band \( (F(3,16)=186.57, p<.001) \) and a significant main effect for lead in the beta frequency band \( (F(3,16)=133.25, p<.001) \), both indicating a decrease in interhemispheric coherence following the same order of leads, but again with a different slope.

Hemisphere
The MANOVA analysis for power only showed a significant three-way interaction between frequency band, lead, and hemisphere \( (F(3,16)=7.93, p<.01) \). Analyses per frequency band yielded no significant power effects for hemisphere. The MANOVA analysis for the intrahemispheric coherence yielded a significant interaction between hemisphere and lead \( (F(3,16)=7.54, p<.01) \), indicating a higher right than left intrahemispheric coherence for the frontal lead. Finally, the MANOVA analysis for the interhemispheric coherence yielded no significant hemisphere effects.
Discussion

The results demonstrate that the EEG alpha power can be modulated by the content of films. A reduction was found in the right frontal to left interhemispheric communication for the alexithymic individuals compared to controls. However, no differences dependent on film content were found between groups. These results are discussed in more detail below.

A decrease of alpha power was found for both emotional films relative to the neutral film. This effect was more pronounced at the parietal leads. Because the films were presented in randomized order and sufficient time was given after the presentation of each video clip to allow subjects to return to a baseline emotional state, the reduction in alpha power was most likely caused by the contents of the films. However, the fact that the reduction of alpha power was more pronounced at the parietal lobes does not exclude the possibility that the effect was caused by a variation in semantic and pictorial content between the emotional and neutral film clips. The parietal lobes play a major role in visual orientation and recognition or formation of abstract concepts, while the temporal and (pre)frontal lobes are more involved in emotion-related processing (Kolb & Whishaw, 1990). Because the emotional content of the films did vary (an interpretation supported by the significant differences between films in the production of emotional words), the reduction in alpha power could also be the result of differences in emotional arousal produced by the films. If desynchronization of the alpha rhythm may be interpreted as indicating higher cortical activation, then this result might indicate increased activation of the brain while watching the emotional films as compared to a neutral film. This interpretation is in line with the study of Schellberg et al. (1990) where an increasing modulation of alpha power for film in the order: neutral, negative-emotional, positive-emotional was found. The interaction for alpha power between film and lead was, however, not significant in the Schellberg et al. study.

We also demonstrated that alexithymic individuals have reduced coherence between the right frontal lobe and the left hemisphere compared with controls (non-alexithymic individuals), independent of film. It is of interest that the coherences for alexithymic individuals between either frontal region and the contralateral hemisphere are approximately equal, while for non-alexithymic individuals the right frontal region is more coherent with the left hemisphere than the left frontal region with the right hemisphere. A higher interhemispheric coherence between the right frontal region and the left hemisphere was also found by Tucker et al. (1986), when the intra- and interhemispheric coherence topography was measured for 14 healthy right-handed men. Hopftman and Davidson (1994) described a meta-analysis of Marzi et al. (1991). In this meta-analysis simple reaction-time studies were analyzed, measuring the Inter-Hemispheric Transfer Times (IHTT) for visual information. The meta-analysis suggested that transfer of simple information, as measured by the IHTT, is faster.
from the right hemisphere to the left hemisphere, than in the opposite direction (13 of the 16 studies). Intuitively, faster IHTT seems compatible with the idea of higher interhemispheric coherences as measured in the EEG. Hence, the IHTT results are in line with the coherence results of Tucker et al. (1986), and the coherence results for the non-alexithymic individuals of the present study. Based on these results, the conclusion can be drawn that the interhemispheric transfer deficit in alexithymic individuals is manifested by the absence of a higher level of interhemispheric communication between the right frontal lobe and the left hemisphere than between the left frontal lobe and the right hemisphere.

In the study of TenHouten et al. (1987, 1988), the interhemispheric alpha band coherence was measured for commissurotomized patients, and neurologically intact controls while they watched a symbolic emotional film. In their study, indications were found for lower interhemispheric coherences in the commissurotomized patients for the frontal, parietal, and temporal leads. For the central leads, a higher interhemispheric coherence was obtained for commissurotomized patients. Because coherence is considered here as a measure that reflects differences in structural connectivity among cortical areas, corpus callosotomy patients may be expected to demonstrate lower interhemispheric coherences for all regions of the brain (anterior and posterior). Thus, a comparison of the results of TenHouten et al. with those of this study, where coherences were measured in neurologically intact alexithymic subjects, is problematic.

The interpretation of coherence results requires great care (French & Beaumont, 1984). If coherence reflects differences in structural connectivity between cortical areas, then the results of this study indicate reduced cortical connectivity between the right frontal lobe and the left hemisphere for alexithymic individuals compared with controls. Because the corpus callosum appears to be necessary for the transfer of higher level (more complex) information between the hemispheres (Hoptman & Davidson, 1994), there is some indication for reduced corpus callosal function between the right frontal region and the left hemisphere in Type II alexithymic individuals.

In the integrated cortical neural network, hypothesized as responsible for the highest neurophysiological level of emotional processing, modules located in the right hemisphere, particularly the right frontal region, are probably more involved in the (nonverbal) regulation of emotional arousal and the regulation of autonomic response to emotional stimuli, while modules located in the left hemisphere are probably more involved in the (verbal) cognitive and communicative aspects of emotions (Fuster, 1989; Gainotti et al., 1993; Kolb & Whishaw, 1990). Note that the general neurophysiological model for alexithymia posits that alexithymia can be considered to be a disruption in this integrated cortical neural network. Different types of alexithymia can be the result of impairments in different modules or connections within this network. This is in line with Bermond (1995) who makes a distinction between different types of alexithymia dependent on different neurophysiological dysfunctions. In his distinction Type II alexithymia is
characterized by the presence of the emotional experience (transported to the left hemisphere by the anterior commissure) but in the absence of the normally accompanying cognitions (transported to the left hemisphere by the corpus callosum). It is this type of alexithymia, according to Bermond (1995), that could reflect a reduced function of the corpus callosum. Therefore, in the present study the alexithymic individuals were selected for high scores on the capacity to experience emotional feelings, but low on the accompanying cognitions. Consequently, it is expected that this particular group must have an impairment in the (emotional) information transfer from the right frontal region, where the emotionality itself is regulated, to the left hemisphere, where the verbal, cognitive, and communicative aspects of the emotion are regulated. The lower interhemispheric cortical connectivity between the right frontal region and the left hemisphere found in this study for alexithymic individuals compared with controls is in accord with this expectation. This result is also in line with the reduction in interhemispheric alpha band coherence found by TenHouten et al. (1987, 1988) for commissurotomized, and thus alexithymic, patients.

A possible explanation for the small differences in mean coherence values in the alexithymia-by-hemisphere interaction in the present study may be found in the selection of the participants of this study. Although they were extremely alexithymic in the population of first year psychology students, they were not extremely alexithymic when compared to the scores obtained from a clinical group. Another important issue is that no indications have been found for task-related alexithymia effects (no interactions with film). A possible explanation for the absence of any film-related alexithymia effect might be that coherence does not reflect task-related differences (functional coupling) in cortical activation (see also French & Beaumont, 1984). This explanation is supported by the finding that no straightforward film-related coherence effects were found, although a decrease of alpha power, as an indication of activation, was found for both emotional films. This suggests that coherence may only be used as a measure for structural connectivity between cortical regions. This is in line with the view of Lopes da Silva (1991) that EEG signals reflect more readily changes in the state of the underlying networks, particularly if these changes involve a relatively large area, than specific aspects of the information being processed. This explanation does not exclude the possibility that task-dependent alexithymia effects do exist. Another explanation for the absence of any film-related alexithymia effect might be that alexithymic individuals have a generalized deficit in interhemispheric transfer involving all types of information. This explanation is partly in line with the results of Zeitlin et al. (1989) who found a bidirectional interhemispheric transfer deficit for alexithymic individuals in the transfer of sensorimotor information.

In conclusion, it was found that alexithymics have reduced coherence between the right frontal lobe and the left hemisphere. It would be worthwhile to repeat this study with selection of the subjects from a clinical population of alexithymic patients.
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References


Alexithymia: A disruption in a cortical network


General Discussion

The main research question of this thesis was whether individual differences in cognitive avoidance of (stress-related) negative emotions are reflected in individual differences in physiological responses to mental stress. An emphasis was placed on sympathetic, cardiac vagal, and central physiological responses. A literature review and two studies were performed to be able to improve on the measurement of autonomous physiological responses to mental stress. Three studies were then performed, each with a specific group of participants who were selected on an emotional coping style that has been related (in the literature) to deviant autonomous physiological responses to mental stress. For all studies, mental stress has been experimentally induced in the laboratory. The conclusions of the review and the main results of all 5 studies described in this thesis are summarized below. First, theoretical and methodological issues regarding some measures of autonomous physiological response to mental stress are discussed. Secondly, the studies regarding the relationship between psychological traits and physiological responses to mental stress are discussed. Thirdly, a reasonable synthesis of the main results is attempted. This synthesis emphasizes cognitive avoidance of negative emotions and its reflection in the peripheral versus central physiological responses to mental stress. Finally, some recommendations are made to improve the methodology of future studies on SNS, SAM, HPA, and PNS responses to mental stress.

Methodological and theoretical issues in studying physiological responses to stress

The review in chapter 2 discussed the evidence for differential sensitivity of the SAM and HPA axes to specific psychological characteristics of a stress situation. A dualistic model has been put forward in the literature in which mental effort induces a rapid increase of catecholamine levels mediated through the SAM axis, while (perceived) distress triggers (additional) cortisol responses mediated through the HPA axis (e.g., see Lavallo & Thomas, 2000; Lundberg & Frankenhauser, 1980). This situational specificity is tacitly assumed to reflect a broader (dispositional) difference in the preferred emotional coping style (see Henry & Stephens, 1977). Notwithstanding the fact that the dualistic model of SAM and HPA reactivity has been an accepted standpoint for more than two decades (i.e., starting from Henry & Stephens, 1977), it is concluded that several
theoretical and methodological problems exist for the human studies that have been performed to demonstrate this model. Chapter 2 presented a more parsimonious model for the observed results of these human studies, which is more in line with theoretical notions about the central and peripheral coupling of the SAM and HPA axes. This alternative model explains the observed SAM and HPA response patterns by variations in the intensity of mental stress, concurrent muscular activation, and the occupation of glucocorticoid receptors (GR) for cortisol. This model no longer needs the assumption that different psychological dimensions of a stress situation influence the pattern of SAM and HPA responses. However, it does allow for the possibility that only stress situations of high intensity (i.e., surpassing the threshold for reactivity of the HPA axis) lead to high cortisol levels. It also allows for the possibility that previous stress or continuation of the stress situation (i.e., leading to high GR occupation) influences the balance in reactivity of the SAM and HPA axes. It is not unreasonable to suggest that specifically intense or lengthy stress situations would be labeled as ‘distressful’. In practice, therefore, the predictions of the alternative model may not differ strongly from those of the classic dualistic model. However, the new model is believed to be more theoretically robust than the dualistic model.

Although SAM and HPA responses to mental stress have been studied intensively in the past, reactivity of the PNS had, until recently, not been a prime research target. However, during the writing of this thesis, there was a marked increase in the number of publications in the field of psychophysiology and psychosomatic medicine that have used RSA as an index of cardiac vagal tone (e.g., see Bernston et al., 1997; Spalding, Jeffers, Porges, & Hatfield, 2000; Watkins, Grossman, Krishnan, & Sherwood, 1998). Unfortunately, the interpretation of the results of some of these studies may have been clouded by some methodological problems in the use of RSA as an index of cardiac vagal tone. RSA may be estimated by computing the high frequency (i.e., in the respiratory band) heart period power (Bernston et al., 1997). However, some frequency domain heart period power computation methods assume that the data are (at least weakly) stationary, which may not always be the case. The study described in chapter 3 addressed the first main issue in the estimation of cardiac vagal tone by means of RSA: the influence of non-stationarity in the estimation of RSA by means of spectral analyses of heart period data. The error that is made by using discrete Fourier transformation (i.e., a method with an assumption of stationarity) was quantified by comparing heart period power values computed by discrete Fourier transformation with those computed by discrete Wavelet transformation (i.e., a time-frequency method without an assumption of stationarity). This comparison yielded surprisingly small differences (i.e., < 1%) between the power values computed by both methods in conditions of relaxation and mental stress. The differences were only slightly larger for heart period segments classified as non-stationary as compared to segments classified as stationary. It is concluded that the estimation of heart period power values by
frequency analyses based on the Fourier transform is adequate for most psychophysiological designs. The modern time-frequency method of discrete Wavelet transformation is clearly superior (for estimating heart period power values) when additional analyses in the time-frequency domain are required (e.g., in situations where the development of spectral powers in various frequency bands needs to be tracked continuously over time).

Dedicated software has been developed for the estimation of stationarity and for the computation of heart period and respiratory power values by discrete Fourier and Wavelet transformation. This software also generates additional time-frequency information obtained from the Wavelet transform. This software has been written solely for the purpose of the studies reported in chapters 3, 4, and 6. The complete software package and its annotations are considered an appendix to this thesis and have been made available as freeware (download at \{www.psy.vu.nl/vu-ams/software/software.png\}).

The study described in chapter 4 addressed the second main issue in the estimation of cardiac vagal tone by means of RSA: to what extent is RSA determined by factors other than cardiac vagal tone? The results of this study demonstrated that RSA does change as a consequence of stress- or exercise-induced reductions in cardiac vagal tone. However, changes in central respiratory drive, tidal volume, and respiratory rate independently lead to changes in RSA as well. An illustration of changes in RSA that were not related to reductions in cardiac vagal tone is shown in Figure 1. This Figure shows a scatter-plot of heart rate and an index of RSA (computed with discrete Fourier transformation) obtained from a participant (of the study described in chapter 3) with a deviant RSA response to mental stress. The differences in heart rate could not be explained by differences in the beta-adrenergic drive to the heart (estimated with PEP) because the PEP remained almost unchanged during the entire measurement period. Thus, differences in heart rate must have been the result of differences in cardiac vagal tone. Although the level of RSA is normally expected to decrease as cardiac vagal tone decreases, Figure 1 clearly shows two correlation patterns. More insight was obtained after these data were analyzed separately for segments classified as relatively high versus relatively low in physical activity. An index of changes in (vertical acceleration) motility values was (also) obtained from the Vrije Universiteit Ambulatory Monitoring System (VU-AMS) used for performing these measurements. Data segments with a mean motility value below 0.6 gsec were separated from data segments with a mean motility value above 0.6 gsec. This threshold value distinguished (for our VU-AMS device) segments with quiet sitting from segments with walking or turning (the participant has for example walked in between the relaxation and mental stress conditions). The expected negative correlation was found between heart rate and RSA for segments classified as relatively high in physical activity ($r=-.63, n=36, p<.001$), while a totally unexpected positive correlation was found for the majority of segments classified as low in physical activity ($r=.64, n=252, p<.001$). The segments did not
differ in the incidence of non-stationarity, and the selected high frequency interval (i.e., the respiratory band) used for the computation of the RSA values always included the respiratory frequency. Thus, the high frequency power values should have correctly estimated RSA. It is concluded that, for this particular participant, the RSA reactivity to mental stress falsely suggested increased cardiac vagal tone, where cardiac vagal tone actually must have decreased.

![Heart rate - RSA scatter-plot](image)

**Figure 1.** Heart rate - RSA scatter-plot of a remarkably deviating participant.

With the results of the study described in chapter 4 in mind, an increased RSA value during mental stress need not necessarily indicate increased cardiac vagal tone. It may also reflect increased arterial partial pressure of CO₂, increased tidal volume, or decreased respiratory rate. The relative contribution of these determinants to RSA is probably not fixed (i.e., it changes between mental stress, relaxation, and physical activity; see chapter 4) and it probably shows large individual differences (e.g., the participant of Figure 1 versus the bulk of participants described in chapter 4). Therefore, it is concluded that rigid interpretation of reduced RSA in terms of reduced cardiac vagal tone may sometimes be misleading.

*The relationship between psychological traits and physiological responses to stress*

The study described in chapter 5 examined autonomous physiological reactivity and habituation to emotional stimuli in individuals with a repressive emotional
coping style and controls. Although significant effects were found (for all participants) on self-reported affect, skin conductance (used to measure sympathetic reactivity), heart rate, and facial muscle responses to the emotional pictures, no differences emerged between repressors and controls. Additionally, the groups did not differ in habituation of these responses. A disposition towards cognitive avoidance of negative emotions (e.g., a repressive or alexithymic emotional coping style) has often been related in the literature to increased autonomous physiological responses to mental stress (Brown et al., 1996; Linden & Long; 1987; Sifneos, 1973; Schwartz, 1990; Ursin & Olff, 1993; Watson & Pennebaker, 1989; Weinberger, Schwartz, & Davidson, 1979). However, the results of the study described in chapter 5 did not confirm such a relationship.

The study described in chapter 6 examined autonomous physiological reactivity to mental stress in a ‘mirror’ group of individuals that suffer from functional somatic symptoms or somatization disorder (i.e., a medical explanation cannot be found; see Wesseley, Nimnuan, & Sharpe, 1999; Ursin, 1997). In contrast to individuals characterized by a repressive emotional coping style, individuals belonging to this mirror group (that additionally score high on questionnaires that measure trait anxiety) overtly demonstrate their negative affect, both verbally and with somatization (see Watson & Pennebaker, 1989; Wientjes & Grossman, 1994). Self-reported somatic symptoms, experienced tenseness and anxiety, and RSA, PEP, heart rate, and respiratory responses to mental stress and (mild) physical exercise were compared between individuals with numerous functional somatic symptoms and controls. Although large effects in the differences between groups were found on self-reported anxiety and tenseness as well as on self-reported somatic symptoms, the expected group differences in autonomous physiological responses (i.e., in RSA responses) were not found.

As expected, no differences were found between repressors and controls in self-reported affective responses to emotional stimuli (see chapter 5). Repressors do not overtly report their affective responses. However, individuals with numerous functional somatic symptoms did significantly differ from controls in their self-reported affect and in somatic complaining (see chapter 6), and a high and significant correlation was found between scores on the frequency of functional somatic symptoms and trait anxiety ($r=.86, n=36, p<.001$). Thus, these individuals do overtly report their affective responses. In spite of the clear-cut difference in emotional coping, a contrast in the pattern of autonomous physiological reactivity was not found. No evidence was found for a straightforward effect of either repression or somatization on most measured autonomous physiological responses to mental stress. The only exception was a reduced PEP reactivity for individuals with numerous functional somatic symptoms. However, this unexpected effect needs replication before any valid conclusion can be drawn. Thus, individuals with numerous functional somatic symptoms are most likely not characterized by increased autonomous
physiological responses to mental stress. This is in line with previous suggestions that functional somatic symptoms are explained to a much larger degree by psychological mechanisms, as compared to (peripheral) autonomous physiological mechanism (e.g., see Troosters et al., 1999; Wientjes & grossman, 1994; Watson & Pennebaker, 1989; Sharpe & Bass, 1992).

The final study described in chapter 7 was performed to compare alexithymic individuals and controls in the responses to mental stress at the level of the central nervous system. The specific hypothesis was tested that alexithymia reflects a deficit in corticocortical interhemispheric communication (e.g., see TenHouten, Walter, Hoppe, & Bogen, 1987,1988). Differences between repressors and controls have previously been demonstrated in frontal electro-encephalogram (EEG) brain activation (Tomarken and Davidson, 1994). A relationship between individual differences in cognitive avoidance of (stress-related) negative emotions and EEG coherence patterns had, however, not yet been examined. In the study described in chapter 7, EEG-coherence patterns were measured in alexithymic individuals and controls during the presentation of emotional film excerpts. Indications were indeed found that alexithymic individuals have reduced EEG-coherence values between the right frontal lobe and the left hemisphere, independent of the content of the films. Nonetheless, it is concluded that individual differences in cognitive avoidance of negative emotions do have a measurable physiological representation at the level of the central nervous system.

**Synthesis of the main results**

Large individual variability exists in height and pattern of autonomous physiological responsiveness to mental stress situations (e.g., see Cacioppo, 1994; Brownley, Hurwitz, & Schneiderman, 2000). It has been suggested that autonomous physiological responses to mental stress are influenced by the style of emotional information processing (Brown et al., 1996; Linden & Long; 1987; Sifneos, 1973; Schwartz, 1990; Ursin & Olff, 1993; Weinberger, Schwartz, & Davidson, 1979). Nonetheless, the studies of this thesis did not demonstrate a relationship between individual differences in cognitive avoidance of (stress-related) negative emotions (i.e., a repressive emotional coping style) and individual differences in autonomous physiological responses to mental stress. Furthermore, a straightforward relationship between individual differences in functional somatic symptoms and individual differences in autonomous physiological responses to mental stress was not found.

A major limitation of the studies of this thesis is that the responses of other physiological systems that react to mental stress were not measured (i.e., responses of the SAM and HPA axes). Thus, the possibility cannot be excluded that individuals with a repressive emotional coping style or individuals with
numerous functional somatic symptoms differ from controls in the responses of the SAM and HPA axes to mental stress. Additionally, since all participants of the studies of this thesis were young first-year psychology students, these results do not exclude the possibility that in the long term some psychological styles of emotional information processing may become correlated to autonomous physiological responses to mental stress (i.e., for older people).

Assuming that the results presented in this thesis do generalize to SAM and HPA measures and also hold true in older populations, it is concluded that a repressive emotional coping style and functional somatic complaining are not characterized by deviant autonomous physiological responses to mental stress. Nonetheless, individual differences in cognitive avoidance of negative emotions are not necessarily invalidated by the ‘hard’ psychophysiological results of this thesis. Alexithymic individuals, for example, showed significantly reduced EEG-coherence values between the right frontal lobe and the left hemisphere. It is therefore speculated that individual differences in repressive emotional coping or individual differences in functional somatic symptoms complaining do not reflect individual differences in (peripheral) autonomous physiological responses to mental stress, but they do reflect individual (physiological) differences at the level of the central nervous system. For example, the central threshold for detection of somatic sensations, which according to Damasio (1996) resides mainly in the frontal lobes, might be lower in individuals with numerous functional somatic symptoms, either by disposition or as a result of increased attention to somatic sensation during stress situations. In contrast, the central threshold for detection of affective and/or somatic sensations might be impaired in repressors and alexithymic individuals (as evidenced by reduced EEG-coherence values between the right frontal lobe and the left hemisphere for alexithymic individuals).

Methodological recommendations

Discrete Fourier transformation is an appropriate method for the estimation of RSA by computing heart period power values in the respiratory frequency band. However, the modern time-frequency method of discrete Wavelet transformation is clearly superior when the development of respiratory-related heart period power (RSA) needs to be tracked continuously over time. An example of such an application (for a time-frequency method) may be found by analyzing the cardiac vagal contribution to the bi-phasic heart rate response to looking at emotional pictures. The vagal contribution to this relatively fast change in heart rate (i.e., within seconds) could not be estimated with the classic method of frequency analysis using discrete Fourier transformation. However, this information is available in the time-frequency information obtained from discrete Wavelet transformation.
Studies designed to measure changes in RSA as an index of changes in cardiac vagal tone should also measure changes in the beta-adrenergic drive to the heart (e.g., with changes in PEP), changes in central respiratory rate (e.g., with end-tidal partial pressure of CO$_2$ or with an estimation of the transcutaneous partial pressure of CO$_2$; see Garssen, Buikhuisen, Hornsveld, Klaver, & vanDoornen, 1994), changes in tidal volume (e.g., with respiratory power), and changes in respiratory frequency. To correct (changes in) RSA values with (changes in) these measures is especially recommended for studies on patient groups with respiratory-related complaints like asthma and hyperventilation.

The proposed alternative model of reactivity of the SAM and HPA axes (outlined in chapter 2) may (if it holds up) help guide future research on the physiological responses to mental stress. First, the prediction of this model should be tested that the (initial) central GR occupation (in the hippocampus, pituitary, and hypothalamus) influences the balance in reactivity of the SAM and HPA axes to mental stress. This may be experimentally demonstrated by measuring the SAM and HPA responses to mental stress after administration of a placebo versus a drug that occupies the GRs to two randomly assigned groups of healthy participants. It should then be tested whether individual differences in (chronic) GR occupation reflect individual differences in chronic (mental) stress (i.e., that the GR occupation results from chronic activation of the HPA axis). Estimating individual differences in GR occupation may be problematic. One approach would be to test individual differences in the effects of administration of a drug that occupies the GRs on the SAM and HPA responses to mental stress. These should be illustrative of the existing individual differences in (initial and/or chronic) GR occupation. Performing these studies might provide evidence for a relationship between chronic stress and specific autonomous response patterns to mental stress.

An open and intriguing question is whether (chronic) GR occupation is in any way also related to central emotional information processing. Such a relationship may ultimately provide a more sophisticated model for the relationship between psychological mechanisms and the balance in SAM and HPA responses to mental stress. For example, Newcomer and co-workers (1999) have already demonstrated that increased cortisol levels (i.e., induced by stress level cortisol treatment) impair memory performance in healthy adults. Thus, future experiments combining assessments of psychological mechanisms, central nervous system functioning, and autonomous responses can extend our understanding of the complex relationship between psychological mechanisms and physiological responses to mental stress.
References


Samenvatting


Het oorspronkelijk onderzoeksplan voor dit proefschrift bestond uit het testen van een speculatief idee: individuele verschillen in psychologische afweermechanismen (d.w.z. verschillen in cognitieve vermijding van negatieve emoties) zouden samenhangen met individuele verschillen in de reactiepatronen van de drie genoemde autonome fysiologische systemen op stress. Psychologische afweermechanismen zouden de balans in de afgifte van adrenaline en cortisol, tijdens of na een stresssituatie, beïnvloeden. Een literatuurstudie leerde evenwel dat aan nader onderzoek van deze hypothese (te) veel theoretische en methodologische problemen kleven. Als gevolg daarvan is in dit proefschrift het accent komen te liggen op de relatie tussen psychologische afweermechanismen en de reacties op stress van het parasympathisch zenuwstelsel. Daarnaast komt de relatie aan bod tussen psychologische afweermechanismen en individuele verschillen op het niveau van het centrale zenuwstelsel (in het brein).

Het eerste deel van dit proefschrift gaat in op de theoretische en methodologische aspecten die van belang zijn voor het onderzoek naar autonome fysiologische reacties op stress. In hoofdstuk 2 wordt de literatuur over de balans tussen adrenaline en cortisol in reactie op stress kritisch geëvalueerd. Er is volgens deze literatuur sprake van een dualistisch model: mentale effort leidt tot verhoging van de afgifte van adrenaline (en noradrenaline) in het bloed vanuit het bijniermergsysteem, en mentale distress activeert het bijnierschors-systeem tot additionele verhoging van cortisol. Bovendien wordt verondersteld dat deze situationale specificiteit in de afgifte van adrenaline en cortisol, te generaliseren valt naar disposities (stabiele individuele verschillen). Bepaalde disposities in de voorkeur voor een bepaalde emotionele coping-stijl, zouden van invloed zijn op de balans in de afgifte van genoemde stresshormonen. Evaluatie van de literatuur wijst uit dat er verscheidene theoretische en methodologische bezwaren zijn in te brengen tegen de onderzoeken die het dualistisch model bij mensen hebben trachten aan te tonen. Een alternatief, theoretisch zuiniger model wordt dan ook gepresenteerd. Dit model verklaart de balans in de afgifte van adrenaline, noradrenaline en
cortisol met variaties tussen stresssituaties in de intensiteit van stress, de mogelijk toegenomen spierspanning tijdens stress, en de bezetting van glucocortisosteroidereceptoren (voor cortisol) in het brein. Dit alternatieve model is theoretisch robuuster dan het klassieke dualistische model.

Hoewel de reacties op stress van het bijniermerg- en bijnierschorsysteem in het verleden uitgebreid zijn onderzocht, zijn de reacties van het parasympathische zenuwstelsel lange tijd onderbelicht gebleven. Pas de laatste paar jaar is er aandacht voor reacties van de nervus vagus, een onderdeel van het parasympathisch zenuwstelsel. Met name het gebruik van respiratoire sinus aritmie (RSA) als maat voor de cardiale vagale tonus (waarmee het parasympathisch zenuwstelsel hartslagveranderingen reguleert) is de laatste tijd enorm toegenomen. RSA als maat voor de cardiale vagale tonus, zou evenwel problemen op kunnen leveren. RSA kan geschat worden als de power (variantie) van het hartslagsignaal in de relatief hogere frequentieband (gerelateerd aan de ademhaling). Een veel gebruikte rekenmethode hierbij is Fourier-transformatie. Een nadeel van deze methode is dat de aannamen van niet-stationariteit geschonden wordt, wanneer er (veelal niet stationaire) hartslagdata meer analyseerd worden.

Hoofdstuk 3 beschrijft onderzoek dat als doel heeft om de fout als gevolg van deze schending te bepalen. Dezelfde hartslag-datasegmenten zijn geanalyseerd met zowel de klassieke Fouriermethode als een relatief moderne tijd/frequentiemethode, gebaseerd op Wavelet-transformatie. Wavelet-transformatie kent geen aannemen van stationariteit. De verschillen tussen de beide methodes blijken echter voor zowel stationaire als niet-stationaire data erg klein te zijn (< 1%). De conclusie is dan ook dat de Fouriermethode zonder bezwaren te gebruiken is om hartslag-powerwaarden te bepalen. De Waveletmethode is alleen superieur wanneer de extra informatie die deze methode in het tijd/frequentie-domein oplevert, van belang is.

Het onderzoek beschreven in hoofdstuk 4 heeft betrekking op een tweede probleem bij het gebruik van RSA als maat voor de cardiale vagale tonus; óf, en in welke mate, RSA óók door andere factoren bepaald wordt. De resultaten wijzen uit dat andere factoren inderdaad een sterke invloed kunnen hebben op RSA - onafhankelijk van veranderingen in de cardiale vagale tonus. Veranderingen in de centrale respiratoire drive, in ademhalingsdiepte, en in ademhalingsfrequentie blijken namelijk ook te kunnen leiden tot veranderingen in RSA. De conclusie is dan ook dat veranderingen in RSA niet altijd te interpreteren zijn als veranderingen in cardiale vagale tonus.

Het tweede deel van dit proefschrift gaat over de relatie tussen individuele verschillen in psychologische afweermechanismen, en individuele verschillen in autonome fysiologische reacties op stress. Hoofdstuk 5 beschrijft onderzoek naar verschillen in gerapporteerde affectieve en autonome fysiologische reacties tussen een groep proefpersonen met een repressieve emotionele coping-stijl, en twee controlegroepen (laag en gemiddeld angstige proefpersonen). Mensen die een
repressieve coping-stijl hanteren, worden verondersteld om - ondanks afwezige gerapporteerde affectieve reacties - toch hoge(re) autonome fysiologische reacties te vertonen op emotionele prikkels. De gerapporteerde affectieve en autonome fysiologische reacties op emotionele plaatjes zijn gemeten. Uit de resultaten van dit onderzoek blijkt dat de plaatjes de verwachte gerapporteerde affectieve en autonome fysiologische reacties opwekken bij alle proefpersonen. Er zijn echter geen groepsverschillen gevonden in de gerapporteerde affectieve noch de autonome fysiologische reacties. Evenmin zijn groepsverschillen gevonden in habituatie van de autonome fysiologische reacties. De conclusie luidt dan ook dat er op grond van deze resultaten getwijfeld mag worden aan het bestaan van een harde, robuuste relatie tussen een repressieve emotionele coping-stijl en autonome fysiologische reacties op stress.

Er bestaat echter ook een ‘gespiegeld’ groep mensen. In tegenstelling tot mensen met een repressieve emotionele coping-stijl, zijn zij juist geneigd hun emoties en lichamelijke sensaties in hoge mate te rapporteren. Deze mensen, die veelal ook hoog angstig zijn, leiden aan functionele somatische symptomen of een somatisatiestormis (oftewel, een medische verklaring voor hun klachten is niet te vinden). Het onderzoek beschreven in hoofdstuk 6 heeft als doel om groepsverschillen in gerapporteerde affectieve en autonome fysiologische reacties op stress te meten. Een groep proefpersonen met frequente functionele somatische symptomen wordt vergeleken met een controlegroep bestaande uit proefpersonen die weinig tot niets van deze symptomen vertonen. Het onderzoek toont aan dat angst, gespannenheid en lichamelijke sensatie bij mensen met functionele somatische symptomen in stresssituaties veel sterker toeneemt dan bij personen uit de controlegroep. Ook bij dit onderzoek zijn echter geen duidelijke groepsverschillen gevonden in de autonome fysiologische reacties. Op grond van de onderzoeken en bevindingen zoals beschreven in hoofdstuk 5 en 6, is te concluderen dat er weinig aanwijzingen zijn voor een robuuste relatie tussen zowel repressie van emoties als somatisatie en autonome fysiologische reacties op stress. Functionele somatische symptomen lijken dan ook eerder verklaarbaar door psychologische mechanismen dan door autonome fysiologische mechanismen.

Mensen met alexithieme kenmerken hebben een lage rapportage en duiding van hun emoties, en ook een gering emotioneel inzicht. Het onderzoek zoals beschreven in hoofdstuk 7, toont aan dat er fysiologische verschillen bestaan op het niveau van het centrale zenuwstelsel tussen alexithieme en niet-alexithieme mensen. EEG-coherentiematen (als ruwe maat voor connectie tussen bepaalde gebieden in het brein) zijn gemeten tijdens het bekijken van emotionele en neutrale filmfragmenten. Het blijkt dat de alexithieme proefpersonen inderdaad een lagere coherente hebben tussen hun rechter frontale lob en hun linkerhemisfeer. Deze verschillen waren echter onafhankelijk van het soort filmbeelden. De conclusie is dan ook dat psychologische afweermechanismen wél een meetbare fysiologische reflectie hebben in het centrale zenuwstelsel.
De algemene synthese gaat in op het idee dat de drempel voor waarneming van affectieve en lichamelijke sensaties (op centraal niveau), omhoog verschoven kan zijn bij mensen met psychologische afweermechanismen, en omlaag bij mensen met functionele somatische klachten. Er worden voorts aanwijzingen gegeven over hoe het alternatieve model (zoals beschreven in hoofdstuk 2), te toetsen is.
Dankwoord

Tot slot wil ik iedereen bedanken die een bijdrage heeft geleverd aan het tot stand komen van dit proefschrift. Ik doe dit in chronologische volgorde.

Lieve Pa en Ma: jullie staan aan de basis van mij en daarmee ook van dit boekje. Walter en Jos: jullie hebben dit project (dat echter een totaal andere kant is opgegaan) opgestart; dank voor de begeleiding en jullie bijdrage. Simon: onze samenwerking in het opzetten van de studies (beschreven in H4 en H6) heeft geleid tot hele mooie designs; je verhalen bleven boeien. Birgitte, Léontine, Marte, Marthe, Nicole en Paulien: dank voor jullie hulp in het opzetten en uitvoeren van de studies en (natuurlijk veel belangrijker) voor de gezelligheid tijdens het meten in de catacomben van de faculteit en in Kriterion daarna. De vele proefpersonen die soms nare momenten van echte stress hebben ondergaan: ik hoop dat jullie mij niet naar aanleiding van dit proefschrift alsnog weten te traceren om wraak te nemen. De VU-AMS leesgroep (organisatoren Harriëtte en Tanja), de EPP onderzoeksschool, de systeemgroep van de UvA (Bert) en electronica-werkplaats van de VU (Paul): dank voor jullie bijdrage in kennis en/of voor de mooie meetapparatuur. Alle collega’s en vrienden op de UvA, waaronder Bjørn, Diane, Ellen H, Eveline, Frank, Guido, Mark, Martin van L, Kitty, René en vele anderen: dank voor de gezellige koffie-, lunch-, en andere pauzes. En dan natuurlijk speciaal te noemen mijn kamergenoten van kamer 806: lieve Anouk, Bernet, Stephanie en (later) Anda: wat kan ik meer zeggen dan dat de enige en echte reden dat ik na 2 jaar niet gestopt ben de gezelligheid was (en is) in 806. De vele co-auteurs van wie de namen reeds genoemd zijn per hoofdstuk en de (anonieme) reviewers van de diverse tijdschriften: dank voor jullie bijdrage in het helpen schrijven en verbeteren van de artikelen. Ecco: jouw bijdrage aan dit proefschrift is zonder twijfel het grootst geweest van iedereen (afgezien van die van mijzelf natuurlijk). Je grondigheid, logische aanpak, constructieve feedback en snelheid van nakijken van de door mij geproduceerde teksten hebben menig artikel een ongekende ‘lift’ gegeven. Heel veel dank voor al het werk wat jij hiervoor hebt verzet. Verder wil ik degenen bedanken die een bijdrage hebben geleverd aan het proeflezen van (delen van) dit proefschrift en de uiteindelijke realisatie, waaronder Cedric, Erik, Gayle en Harrie. Tot slot wil ik jullie bedanken die dit nu lezen, want wat is een proefschrift zonder lezers.

Amsterdam, november 2000
STELLINGEN

behorend bij het proefschrift 'Psychological and physiological responses to stress' van Jan H. Houtveen

1 De strikte interpretatie van een verlaging in RSA als een vermindering van cardiale vagale sturing van de hartslag is misleidend.

2 Hoewel discrete Wavelet-transformatie een meer valide methode is voor frequentie-analyse van niet-stationaire data, levert discrete Fourier-transformatie van tijdseries van hartperioden met een normale fysiologische range zeer vergelijkbare powerwaarden op.

3 Stressgerelateerde functionele somatische klachten vertonen geen duidelijke samenhang met perifere autonome fysiologische reacties op stress.

4 Het dualistische model betreffende de reacties van de SAM- en HPA-assen op stressvolle situaties dient te worden heroverwogen.

5 Onderzoek waarbij gekeken wordt naar zowel psychologische, centrale fysiologische als perifere fysiologische (cardiovasculair en hormonaal) reacties op stress wordt ten onrechte zeldzaam.

6 Subjectieve interpretaties van fysiologische maten bij stressonderzoek worden vaak gemaskeerd door hun vermeende objectiviteit.

7 Gewoon maar wat proberen is de manier om verder te komen. Zie de evolutie.

8 Sommige 'succes-is-een-keuze' management-trainingen zijn in feite cursussen verdringing van negatieve emoties.

9 Het opwarmen van de hersenen door GSM telefoons is verkeerd onderzocht: niet de bellers maar de omstanders lopen rood aan.

10 Burnout = in.