Contribution of Psychophysiological Measures to Evaluating Flight Task Workload Under Simulated Conditions

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ABSTRACT

We report findings of a preliminary study on psychophysiological evaluation of seven experienced pilots on 18 flight tasks in a 737-800 Level D simulator. The purpose of this research was to perform a preliminary evaluation of psychophysiological measures as a tool for assessing flight task difficulty and workload in a flight simulator to improve procedures for evaluating the evaluating the safety of possible proposed flight rule changes. The primary aim was to determine whether psychophysiological assessment added detectability of task load differences and predictability of pilot performance over a self-report instrument frequently used for this purpose, the NASA Task Load Index (TLX) (Hart & Staveland, 1988). We have found that the addition of particular physiological measures (heart rate, heart rate variability, movement, or ventilation) each adds significant predictability over the TLX alone for determining both *a priori* task ratings and ratings of task performance. Eye blink frequency also shows promise of usefulness, but was tested on only four subjects, so it could not be evaluated statistically. We additionally have found indications that some simulator tasks can produce levels of hypocapnia (reduction in blood levels of CO_2 to dysfunctional levels, caused by ventilation in excess of metabolic need, synonymous with hyperventilation) that may impair intellectual function, and very high levels of blood pressure in some individuals, which may represent a medical risk. Our preliminary observations also suggest that some pilots with the psychological trait of defensiveness may systematically underreport task load, but show exaggerated physiological reactivity to various flight simulator tasks. We conclude that the physiological load produced by various flight tasks can be evaluated in the flight simulator, and that psychophysiological assessment can add accuracy to determining level of workload posed by various tasks. The algorithms necessary to determine precise physiological cutoffs for determining high workload will require collection of more data. However, tasks producing prolonged hypocapnia or very high blood pressure reactions might be considered risky for routine exposure.

1. RATIONALE

1.1. General rationale

The FAA requires objective measures of flight task difficulty and load in order to evaluate the appropriateness and safety of flight rules. The aim of this study was to evaluate physiological measurement as a tool for assessing flight task difficulty under simulated flight conditions, for possible use in evaluating new flight procedures or proposed changes in flight rules. Additionally, we analyzed the relationship between physiological activity and performance decrements. We evaluated the sensitivity of psychophysiological measures to add prediction of task difficulty and pilot performance over that provided by a simpler and cheaper well-validated self-report measure. We also analyzed data to determine thse occurrence of extreme levels of psychophysiological arousal. Tasks that overload pilots to the points of risking a decrease in performance could pose a safety risk, and regular exposure to unhealthy levels of stress may impose a long-term health risk.

In most studies of pilot workload, the latter has most commonly been assessed using subjective report (Morris & Leung, 2006; Saleem & Kleiner, 2005). Although this type of measure enjoys crew acceptance and is easy and inexpensive to collect, it may not provide an accurate picture of the psychological demands placed on the operator. Subjective reports are prone to biases and memory lapses. Indeed, certain individuals, including many pilots, tend not to reveal or even be sensitive to unpleasant emotional states, particularly when such states may connote weakness (Butcher, 1994; Butcher & Han, 1995). This tendency can lead to underreporting of task difficulty and load. Also, due to the complex nature of flying and the multifaceted nature of the human response to stress and task load, it is unreasonable to expect any single measure to provide a complete assessment of the crew members' functional state. Indeed, the correlation among physiological, self-report, and performance indicators of task load often is rather low

(Rowe, Sibert, Irwin, 1998), and each type of indicator provides a different kind of information relevant to evaluating to workload.

Although performance quality may be the most important “bottom line” indicator of unacceptably high task workload, it is not sensitive to the *potential* risk of high task-load situations, because the rate of failure even in very difficult flight simulator tasks is usually very low, so very many subjects would have to be tested in order to obtain sufficient power to evaluate the task load imposed by a particular task; yet even a very low failure rate may pose unacceptable risk if pilots were frequently exposed to a such high-load situation in civilian aviation, hence the need for a very sensitive measure detecting high task load. In addition to “success/failure” on various tasks (e.g. performing a safe landing in a flight simulator task), performance quality also can be rated according to other criteria (e.g., adherence to standard approved procedures). However, standard procedures for managing various flight situations differ among airlines, and, in particularly difficult emergent situations, one could question whether deviation from standard procedures is indeed a problem, if the outcome is successful. Thus, although measures of performance are important and useful, they can be controversial, and are not sufficient to evaluate procedures that are seriously being considered for standard use. Nevertheless, ratings of pilot performance have great face validity for assessing overload, so, mindful of these limitations, we have included a rating of pilot performance as a measure, in the current study, and the predictability of performance decrements from physiological measures. We also have examined specific physiological prediction of pilot performance ratings, over that provided by self-report alone. Previous psychophysiological research has shown a direct, sometimes curvilinear, relationship between psychophysiological arousal and performance adequacy (Yerkes & Dodson, 1909).

Another reason for examining physiological measures is to examine possible health risks. Exposure to frequent, prolonged, or severe stress can pose a risk to health. Identifying procedures that could pose such risks would be helpful for preserving health and well-being (McEwen, 1998, 2005; McEwen & Lasley, 2003; McEwen & Wingfield, 2003).

This study examines these relations and specifically evaluates the contribution of psychophysiological recordings to assessment of pilot workload, over that provided by self-report alone.

1.2. Workload, stress, and psychophysiology

Stress. Stress is a multidimensional phenomenon. It is sometimes assessed as a stimulus and sometimes as a response, and, as a response, it takes many forms. The stress response is often defined as a state of preparedness for action, including modulatory responses the body may emit to preserve homeostasis. Thus although sometimes the stress response is defined as the “fight-flight” reaction (e. g., increases in heart rate, blood pressure, muscle tension, etc.), it is sometimes seen as the opposite (low blood pressure, fatigue, etc.), produced by overactive responses that *modulate* the body’s preparation for action, or a “giving up” pattern of task withdrawal. The particular dimensions of stress may thus include reactions that are sympathetic and parasympathetic, inflammatory and anti-inflammatory, energizing and quieting. The psychological and physiological components of stress vary in healthy individuals, in response both to stimulus conditions as well as to various rhythmic cycles that often reflect the health of various self-regulatory mechanisms. When, for either physical or psychological reasons, the body becomes less adaptable, the individual may no longer be as flexible in responding to various environmental demands, but may show stereotypical reactions both during rest and in response to stimulation, with, for example, blood pressure, immune, or inflammatory function that is either chronically high or low, or a lack of behavioral flexibility and problem solving. This can produce discomfort, decreased performance efficiency, and, eventually, danger to health.

A "stressor," then, might be considered any stimulus or condition that produces a physiological or behavioral response that requires coping action. Although usually we think of such stimuli as coming from the environment (physical or emotional demands) they also can emanate internally (e. g., hunger, disease, etc.). Defined this way, we are *continuously* bombarded by various stressors. If the body is adaptive and our behavioral repertoire sufficiently skilled and flexible, we do not usually consider such changes in demand to be deleterious or even unpleasant. Indeed, they are the stuff of life, without which life would be less interesting, and our ability to cope may deteriorate through disuse.

Stress demands, with respect to homeostatic and coping capacity, have been defined by McEwen (2005) as "allostatic load." The severity of a stress and the length of exposure both contribute to increasing allostatic load, until the body is no longer able to manage the stressors without dysfunction: deterioration in performance, development of symptoms or illness. To this must be added the individual's characteristic response to coping with stress. Some people are constitutionally more physiologically reactive to stress and vulnerable to stress exposure. Characteristic patterns of autonomic reactivity may have a genetic component (Finley et al, 2004; Lensvelt-Mulders, et al, 2001), which can interact with life experience and stress to produce heightened adult reactivity and vulnerability to emotional or physical disease (Nelson et al, 2005; Kopin, 1995; McEwen, 1998).

The individual's behavioral and psychological response to stress may affect behavioral and physiological adaptability. Some people may be hypersensitive to stress symptoms, including physical symptoms and overreactive to them (Aronson et al, 2006; Chen et al, 2006; Posey, 2006), while others may minimize them. Mechanisms for coping with unpleasant emotional states may include active coping with the stressful situation, but also may include emotion-focused coping responses including denial, intellectualization, etc. The effectiveness of the individual's physiological and psychological/behavioral coping repertoire determines the extent to which the person may be at risk for deleterious stress effects.

Defensiveness as a moderator of self-report and physiological stress responses. A well-studied emotional coping style that is related to stress vulnerability is that of "defensiveness", often measured by the Marlowe-Crowne Social Desirability Scale (Crowne & Marlowe, 1960), described below. Defensiveness is a coping style in which people tend to present themselves in a socially desirable manner. It is characterized by avoidance of threatening stimuli and minimization of negative affect. Defensive individuals tend to report lower levels of stress, anger, or anxiety on self-report measures, but *highe*r levels of heart rate and blood pressure levels and reactivity and arousal (Asendorpf & Scherer, 1983; Feldman et al, 2002; Jamner et al, 1988; Miller, 1993; Shapiro et al, 1993, 1995, 1996; Weinberger et al, 1979), electrodermal activity (Benjamins et al, 1994; Tomaka et al, 1992; Weinberger et al, 1979), and muscle tension (Weinberger et al, 1979). Defensiveness also has been associated with elevated salivary cortisol (Brown et al, 1996) and cholesterol levels (Niaura et al, 1992) and lower respiratory sinus arrhythmia (Broomfield et al, 2005; Fuller, 1992; Pauls et al, 2003; Movius et al, 2005). Autonomic effects, such as chronic sympathetic arousal, may directly contribute to the onset or exacerbation of disease among defensive individuals. Studies from our laboratory found that defensive individuals with asthma tend to show exaggerated stress-related bronchoconstriction (Feldman et al, 2002) although they tend to *report* fewer respiratory sensations when exposed to an external respiratory resistive load (Isenberg et al, 1997). Dissociation between physiological and self-report indices of anxiety or stress is magnified among people who score high on defensiveness (usually the MCSDS) (Contrada et al, 1997a,b; Newton & Contrada, 1992; Shapiro et al, 1995). Given the systematic association between defensiveness and high sympathetic/low parasympathetic activity and simultaneous association with low self-report of anxiety or stress, the dissociation between autonomic and self-report measures would be expected to decrease when measures of repressive coping are factored in.

Acute vs. chronic stress. A particular widely studied distinction among various stress responses has been that between *acute* (or *state*) stress and *chronic* stress. Laboratory studies of stress have mostly tended to examine acute situations that tax the individual's physical or behavioral capacities (e. g., temperature (Damato et al, 1968; Wilson & Ray, 2004), gravitational (Brown et al, 2004; Watenpaugh, et al, 2004), or chemical exposure (Spiekstra et al, 2005), situations that require behavioral responses that are at or beyond the individual's level of knowledge or skill, e. g., social skill challenges (Childs et al, 2006; Richards et al, 2005; Rohleder et al, 2006; Uhart et al, 2006)), difficult computational or cognitive tasks (Uhart et al, 2006; Wirtz et al, 2006) , etc.). Such tasks reliably produce increases in catecholamine (Frankenheuser et al, 1976; Lenders et al, 1988) and steroid production (Grunewald et al, 2004; Oswald et al, 2006), increased sympathetic arousal (Middlekauff et al, 1997; Pike et al, 1997; Schommer et al, 2003), decreased vagal tone (Lehrer et al, 1996; Mezzacappa et al, 2001; Terkelsen et al, 2004), self assessments of anxiety or stress (Noto et al, 2005; Gramer et al, 2006), etc. Under some circumstances the degree of stress may degrade behavioral ability to cope with the tasks that are presented, and task failure may further exacerbate the physiological response (Kline, 2000; Noteboom, 2001).

Chronic stress has been assessed both by examining individuals with stress-related *disorders*, such as anxiety, insomnia, some of the physiological concomitants of the stress response, etc., or by examining individuals in situations that are known to elicit stress over a number of days or exposure to war or natural disaster (Lin et al, 2001; Lampert et al, 2002).

We should note that "chronicity" of stress is an inexact term. Two weeks of stress for an adult at examination time may have different effects from years of neglect of an infant in a dysfunctional family, or years of economic deprivation. McEwen's theory of "allostatic load" (McEwen, 2005; McEwen & Wingfield, 2003) suggests that damaging effects on the body may occur in response to wear and tear from either frequent or enduring stress, combined with inadequate coping capacity.

Complexity of the stress response. Perhaps for the various reasons described above, the various cognitive, behavioral, and physiological characteristics of the stress response often do not correlate highly with each other, either within or between individuals. A self-report of stress or anxiety may sometimes be related to sympathetic arousal, but sometimes to parasympathetic dominance, and sometimes be unrelated to any psychophysiological variable.

Thus, the morphology of the stress response is complex. A perfect relationship between "stressful" *stimuli* and "stress" *responses* does not exist, various environmental stimuli may produce different stress responses, and the morphology of the stress response may differ among individuals, and at different times within individuals.

1.2.1. Workload and psychophysiological assessment

Physiological measures have sometimes been touted as more "objective" measures of workload than self report measures, because they are not subject to the same inherent biases (e.g., a tendency to minimize difficulties) (Weimann, 1989). Although there is some validity to this argument, we prefer to view physiological reactivity as an equally valid but *different* measure of stress and workload, with a unique relationship to task performance that may be somewhat independent of self-reported load. Indeed, because assessing self-report of load is so much easier and more inexpensive than psychophysiological assessment, we would assume that psychophysiology would only be useful operationally if it added significant discrimination of task load and prediction of pilot performance, over that provided by the latest self-report methodology.

However, physiological systems respond in highly individual and complex ways to both physical and mental load, and even to psychological *anticipation* of such load, as in classical conditioning, and emotional response to such anticipation (Stegen, DeBruyne, Rasschaert, Van de Woestijne, Van den Bergh, 1999). Additionally, some physiological indices (e.g., heart rate, respiration, and blood pressure) are very responsive to changes in metabolic need created by physical exercise (Samsel & Schumacker, 1991) as well as by emotional responses and anticipation of load, while others, such as heart rate variability (Friedman & Thayer,1998; Gilissen, Koolstra, van Ijzendoorn, Bakermans-Kranenburg, & van der Veer, 2007; Pauls & Stremmler, 2003; Yoshizawa, Sugita, Tanaka, Masuda, Abe, Chiba, Yambe, Nitta, 2004), may be particularly sensitive to psycho-emotional reactions (Tomoika, Kobayashi, Ushiyama, Mizuno & Ohhashi, 2005).

1.2.2. Psychophysiological assessment under operational conditions

Some individuals respond in *particular* physiological systems (e.g. heart rate, breathing, muscle tension, blood pressure, etc.) to *various* kinds of environmental demands, but may not show reactions in other physiological systems (Lacey, Bateman, Vanlehn, 1953). Additionally, however, on the average, specific kinds of situations and demands also do tend to produce specific patterns of psychophysiological change (Hinz, Seibt, Hueber, Schreinicke, 2000). In this report we emphasize two measures, ventilation and cardiovascular activity. These measures are sensitive to both psychological and physical demands, can easily be measured in the aircraft simulator, and have been used as workload measures in other studies of aviation workload (Hankins & Wilson, 1998; Skinner & Simpson, 2002; Svensson & Wilson, 2002; Wilson & Russell, 2003;). We also assessed gross motor activity and eyeblink activity, both of which are systematically affected by task load, and are part of the body's response to workload and stress.

We should keep in mind, however, that in taking these particular measures, we are not looking at an individual's overall level of "arousal", but just the reactions in particular physiological systems. A unidimensional concept of "arousal" or "activation" does not adequately describe psychophysiological response to stimulation, because various indices of arousal are often decoupled from one another. For example, two kinds of "arousal" have different psychophysiological profiles. When paying close attention to environmental stimuli, heart rate and various indices of ventilation tend to decline, while they increase during attention inward or task directed activity (Fredrikson, Dimberg, Frisk-Holmberg, 1981).

Despite these complexities, various combinations of psychophysiological measures do present a picture of the organismic response to stress, as do convergences among psychophysiological, self-report, and performance measures of workload. If various measures point in the same direction, we have more confidence in interpreting a more general physiological change.

For example, one study systematically examined heart rate, heart rate variability, and eyeblink activity during a variety of low and medium work-load flight tasks in a single-engine piston Piper Arrow (PA-28) aircraft (Hankins & Wilson, 1998). They found that heart rate and both high- and low-frequency heart rate variability discriminated levels of flight task difficulty, with heart rate being slightly more sensitive among these three highly-correlated measures. However, in general, they conclude that HRV was not sensitive to variations of in-flight mental workload demands and that greater differences in task load may be necessary to see effects, Eyeblink activity decreased in tasks requiring a high degree of visual scanning. Verwey and Veltman (1996) also found that pilot heart rate more clearly differentiated among the flight segments and presumably different workload demands. Backs, Ryan, and Wilson (1994) used a tracking task that factorially combined two levels of physical workload with three levels of perceptual/cognitive workload and found that blink rate did not differ among the six tracking workload conditions. They concluded that respiration and certain heart activity measures did, in fact, differentiate among the workload conditions. Thus, their work suggests that blink rate may be most useful as an index of the presence of workload, but not a good diagnostic choice for discriminating among levels of demand.

Overall, these studies provide support for the notion that respiration (rate, depth) is sensitive to workload demands when compared to baseline-resting conditions. There is an increase in respiratory rate and a decrease in depth when workloads are compared to rest. Also, there is some evidence that respiration may be diagnostic for levels of workload.

Fahrenberg and Wientjes (2000) ranked cardiovascular measurement as the most suitable for field studies due to its reliability, unobtrusiveness and ease of recording. Of the studies in this review, almost all used one or more indexes derived from heart activity, and many studies combined this with other physiological indexes. The earlier literature reports a consistent pattern of cardiovascular activity from laboratory and field studies; heart rate increases and heart rate variability (HRV) decreases as a function of increases in cognitive workload (Wilson, 1992).

Veltman and Gaillard (1998) used pilots in a flight simulator with a flight scenario with 4 levels of maneuvering/pursuit difficulty. They measured heart period ("cardiac interbeat interval," or "IBI") and mid- and high-band HRV. Comparisons among the levels of task difficulty found that IBI was diagnostic, with IBI decreasing (faster HR) as the task difficulty increased. Tattersall and Hockey (1995) examined flight engineers in a flight simulator using HR and the mid- and high-bands of the HRV spectrum. The flight phase was divided into the takeoff/landing segment. Compared to a baseline condition, HR increased and HRV decreased during flight segments. During the flight segments, HR was higher during takeoff/landing than the in-flight cognitive tasks.

Backs, Lenneman and Siccard (1999) used pilots in a Boeing 747 simulator with low and high workload scenarios. Five segments of the two flight scenarios (takeoff, top of climb, cruise, approach, and landing) were analyzed. Four cardiovascular measures were derived: Heart Period (HP, interbeat interval), low-frequency HRV, high-frequency HRV or Respiratory Sinus Arrhythmia (RSA), and Residual Heart Period.[1] HP was shorter (faster HR) for the high workload scenario. Additionally, HP increased (slower HR) from takeoff to the cruise segment. HRV changes across flight segments are consistent with HP with suppression of HRV with higher workloads.

In summary, work in flight simulators indicates that heart rate increases, interbeat interval decreases and heart rate variability decreases with increased workload demands. This is clear when a resting baseline is contrasted with workloads, although HRV differences among levels of task load are less clear. Mean HR and IBI seem to show evidence of differentiating among mental load demands, distinctions are not significant for low-frequency HRV.

1.3. Self-report of workload: NASA's TLX

The TLX scale (Hart & Staveland, 1998) is a well-validated scale that provides an overall workload score based on a weighted average of ratings on six subscales: Mental Demands, Physical Demands, Temporal Demands, Own Performance, Effort, and Frustration measures workload. The Task Load Index has been tested in a variety of experimental tasks that range from simulated flight to supervisory control simulations and laboratory tasks. The derived workload scores have been found to have substantially less between-rater variability than one-dimensional workload ratings, and the subscales provide diagnostic information about the sources of load. In this study we have used the TLX to assess self-reported workload, and evaluate the usefulness of psychophysiological measures based on their ability to increase prediction of known task workloads and pilot performance, over the prediction offered by the TLX alone.

1.4. Psychophysiological assessment

[1] LF and HF frequency ranges are defined below in paragraph 1.4.1.2 (Table 1).

In the following section we review the rationale for particular psychophysiological measures employed in the present study.

1.4.1. Cardiovascular response

The heart and the vascular system respond to both metabolic need and to anticipation of such need. Increased muscular activity, for example, requires greater oxygen intake and transport. This triggers reflexes designed to increased ventilation, heart rate, blood pressure, etc. Similarly, even *anticipation* of changed metabolic need produces similar changes in physiology. Thus the well-known "fight or flight response", which is physiologically appropriate for combat or flight, may be elicited by other everyday stressors requiring neither of these activities, but producing a vegetative response that may be more appropriate for them than for the social stressors that we more commonly experience. Evolutionary demands have apparently determined that such anticipatory physiological response is adaptive in practically all animals, including humans.

1.4.1.1. Heart rate (HR)

HR is the most widely used physiological indicator of workload and task related strain in studies of commercial and military pilots. Faster HR has been observed during high-workload flight segments such as takeoff and landing. Faster HR has also been found for the pilot in control than for other crew members (Roscoe, 1975). Discrepancies are often found between HR and the subjective workload ratings provide useful data (Lindqvist, Keskinen, Antila, Halkola, Peltonen,Valimaki, 1983), indicating that the two kinds of measures are sensitive to different aspects of flying and the crew members' responses to them (Bonner & Wilson, 2002). Roscoe (1992) concluded that the main determinant of HR response in experienced pilots, in the absence of physical effort, is workload. Lindholm and Cheatham (1983) demonstrated that HR is also sensitive to practice effects where over trials, HR decreases while level of pilot performance increases. However, at times, HR changes during flight may depend on specific environment stresses and physical demands associated with flight, and thus sometimes may reflect these factors to a greater extent than to mental workload; indeed HR is likely to be influenced largely by ongoing metabolic demands and individual metabolic differences (Backs, 1995). However, all of these demands are components of total allostatic load, so we consider HR to be a central measure of workload.

1.4.1.2. Heart rate variability (HRV)

In recent years HRV has been used with increasing frequency for analyzing mental workload in simulated work situations and flight-related studies (Aasman, Mulder, Mulder, 1987; Jorno, 1993; Jorno, 1992; Veltman & Gaillard, 1998).HRV consistently responds to changes from rest to task conditions and to a range of between-task manipulations (Aasman, Mulder, Mulder, 1987; Althaus, Mulder, Mulder, Van Roon, Minderaa, 1998; Bortoluss, Hart, Shively, 1989; Hart & Hauser, 1987; Jorno, 1993; Kramer, Sirevaag, Braune, 1987; Lindqvist, Keskinen, Antila, Halkola, Peltonen, Valimaki, 1983; Nickel & Nachreiner, 2003; Sirevaag, Kramer, Wickens, 1993; Saguragi & Sugiyama, 2004; Tattersall & Hockey, 1995; Veltman & Gaillard, 1998; Wilson, 1993).

A number of studies have found association between low-frequency HRV (LF HRV, i.e., oscillations within the range of 0.05 - 0.15 Hz) and changing levels of user effort. LF HRV is thought to be influenced by both the sympathetic and parasympathetic systems (Bernston, Bigger, Eckberg, Grossman, Kaufman, Malik, Nagaraja, Porges, Saul, Stone, van der Molen, 1997). It also is affected by the baroreflex system (Eckberg & Sleight, 1992). The center point of the band, accounting for most of the variance within it, is usually at a frequency of ~0.10 Hz component, so this band is sometimes referred to as the 0.1 Hz band. Suppressing the baroreflex allows blood pressure to rise during periods of metabolic need, as occurs during physical exercise, and during anticipation of such exercise, as occurs in the fight-flight reflex. Both conditions may occur in high-workload situations.

LF HRV is suppressed under task conditions requiring mental effort (Aasman, Mulder, Mulder, 1987; Mulder, 1986; Mulder, Van Roon, Althaus, Veldman, Laumann, 2002; Tattersall & Hockey, 1995; Veltman & Gaillard, 1996; Veltman & Gaillard, 1998; Wilson & Fisher, 1991) but increases with boring, simple, or repetitive tasks (Schellekens, Sijtsma, Vegter, Meijman, 2000; Egelund, 1982). One study found that decreases in LF HRV are more sensitive to increases in workload than HR increases (Wierwille, Rahimi, Casali, 1985). When tasks become so difficult that an individual “disengages” from the task, the result is a sharp increase in LF HRV (Rowe, Sibert, Irwin, 1998; Aasman et al, 1987; Bodrow, 1975), thereby making HRV (LF band) sensitive not only in detecting the effects of increased workload, but also the point at which task difficulty would result in participants’ disengagement. Used in conjunction with other design tools, HRV may be an aid in both forecasting and diagnosing problematic interfaces. As per the recommendation of Mulder (Mulder, Wijers, Smid, Brookhuis, Mulder, 1989), task periods must last at least five minutes to reliably assess LF HRV.

There is less research on the relationship of other HRV frequency bands to mental load. However, there is theoretical reason to examine high frequency (HF) HRV (0.15-0.4 Hz). Heart rate oscillations in this frequency range reflect parasympathetic influences. The HF band encompasses the frequency band for normal adult respiration, and largely reflects respiratory sinus arrhythmia, the changes in heart rate that accompany breathing. Inhalation is associated with increases in HR and exhalation with decreases. These changes are mediated by activity of the vagus nerve, which is part of the parasympathetic nervous system (Porges, 1992). HF HRV increases during sleep and relaxation, and decreases during effortful mental activity (Backs, Ryan, Wilson, 1991; Delaney & Brodie, 2000; Mulder et al, 1992; Laskar, Iwamoto, Toibana, Morie, Wakui, Harada, 1999;).

There is little literature on the relationship of very low frequency (VLF HRV, 0.005 – 0.05 Hz) to task involvement and load, although the “residual” HRV activity described by Backs et al primarily falls within this range. Oscillations in the VLF HRV band reflect effects of the sympathetic nervous systems on HRV, and also may be an important indicator of stress, mental and behavioral activation, and task involvement. VLF HRV might be expected to increase during both anxiety and high task demand. This frequency band is explored in the current research, although its interpretation is clouded by the brevity of the tasks. Since some VLF oscillations may occur only once or twice within a 5-min task, the fourier analysis does not distinguish between true oscillations and reactions to specific stimuli, or shifts in level of basal heart rate. Pilot research in our laboratory suggests that mental effort increases VLF HRV, although it is difficulty to distinguish between true increases in VLF *oscillations* and shifts in level of arousal, both of which may occur during exposure to stressors.

Table1. Heart Rate and Heart Rate Variability Assessment

Measure	Abbrev-iation	Interpretation and measurement
Heart Rate (HR)	HR	Average inter-beat-interval (IBI) or R-spike to R-spike interval (RRI), Heart Period (HP) (in milliseconds); or heart rate (beats per minute)
Heart Rate Variability	HRV	Total variability in heart rate, often measured by the standard deviation of nonartifactual interbeat intervals, not contaminated by extrasystolic or missed heartbeats. Other measures of dispersion also are used.
Very Low frequency	VLF HRV	Heart rate variability in the frequency band of 0.005-0.05 Hz. This is under control of the sympathetic nervous system, and may reflect thermal control and baroreflex control of blood pressure through changes in vascular tone
Low frequency band	LF HRV	Heart rate variability in the frequency band of 0.05-0.15 Hz. This is usually under control of both the sympathetic and parasympathetic nervous systems, and may reflect thermal control and baroreflex control of blood pressure through changes in heart rate. It includes the 0.10 Hz component. It is sometimes called the Traube-Hering-Mayer wave, and is inversely associated with mental workload in aviation research.
High frequency band	HF HRV	Heart rate variability in the frequency band of 0.15-0.4 Hz. This is under control of the parasympathetic nervous system, and is associated with respiratory activity. Although respiratory sinus arrhythmia usually occurs within this band, it may occur at other frequencies if an individual breathes at a rate that is outside this frequency band.

1.4.1.3. Blood pressure

Blood pressure also is known to increase during stress, although there is a large amount of individual variability in this response (Rose & Fogg, 1993; Rose et al, 1978; Vogt et al, 2006), and in increasing task difficulty among pilots in a flight simulator (Veltman & Gaillard, 1996, 1998). Greater blood pressure reactivity to such stress is associated with familial history of hypertension, and may be a characteristic of people prone to development of this disease, as has long been thought (Hines & Brown, 1936). Similar findings have been obtained among healthy people during computer work (Hjortskov et al, 2004), in employment situations with low control over workflow (Malamed et al, 1998) and in various laboratory tasks (Papadelis et al, 2003; Vincent et al, 1996). Because blood pressure assessment requires periodic inflation of a cuff, it may interfere with pilots' concentration; it is not inobtrusive. We therefore took this measure shortly *after* each flight task, although we are mindful that this may have decreased sensitivity of the measure, because task-related blood pressure changes can occur quickly, and may subside by the time each task concludes.

1.4.2. Respiration

Respiration is one of the body's important mechanisms both for adapting to environmental demand and for maintaining internal balance and homeostasis. Most obvious, of course, is its oxygenation function. All tissues need oxygen to function. However, subtle changes in activity of various tissues changes their rate of metabolism, thus leading to a greater or lesser need for oxygen, as well as elimination of metabolic by-products, principally carbon dioxide (CO_2). Various sensors communicate metabolic need to the brain, which then regulates ventilation to meet the needs of the entire body.

At times, however, immediate change in ventilation may not be sufficient for maximal adaptation. Some conditions, such as sudden intense, prolonged muscular effort (as in the "fight-flight" response), may require a reserve store of oxygen for maximum performance. Thus the body *anticipates* metabolic need, through a process long-studied as "classical conditioning", where various environmental cues for danger may trigger increased ventilation *before* increased metabolic need occurs. Such responses are part of preparation for various stressful situations. Ventilatory response may be affected both by actual physical demand as well as by anticipation of demand which, in turn, may be affected by various cues (e.g., in the aviation situation, anticipation of need to think fast, make decisions, and take quick actions), as well as by various personality factors, which may determine how one interprets the severity and immediacy of stressors. Although professional airplane pilots are selected and trained to respond methodically and coolly to most anticipated events requiring response from them, the respiratory response is an important factor in both maximizing performance and maintaining health, and should be seen in this population as well. Task-related decreases in blood levels of carbon dioxide have been noted among healthy people (Ley & Yelich, 1998; Wientjes, et al, 1998), as well as during anxiety and stress (Van Diest et al, 2001, 2006).

Respiration is involved in other aspects of human function as well as ventilation, however. Some of these other functions may *affect* ventilation. Most obvious is speech. Speech slows respiration and prolongs exhalation. This pattern may, in turn, downregulate the fight-flight preparedness, unless partial compensation occurs by increased *depth* of breathing. For this reason, we measure not only respiration *rate*, but volume of breathing averaged across each minute ("minute volume ventilation", MVV) in order to assess total ventilatory response. When changes in MVV accurately track changes in metabolic need (due to changes in physical or mental activity that change metabolic rate), partial pressure of carbon dioxide in the blood (pCO_2) remains relatively constant. However, the system is not exactly equilibrated, such that small changes in pCO_2 often do occur as the respiratory system adjusts to changes in metabolic need (from exercise, stress, sleep, relaxation, etc.), often, in our experience, in the direction of decreased pCO_2, which would occur where ventilation exceeds metabolic need. MVV can be affected by changes in respiration rate, changes in force of inhalation, and changes in depth of respiration. Inspiratory flow rate is often used as a measure of respiratory drive. The faster the inspiratory flow, the greater the ventilation.

Other aspects of ventilation are involved in other regulatory processes. Respiration also produces a regular *rhythm*, which can be measured in organs throughout the body. One of the most prominent of these is respiratory sinus arrhythmia (RSA) in the heart: increases in heart rate associated with inhalation, and decreases associated with exhalation (although often displaced from respiration by a pronounced phase shift during normal respiration) (Gilad, Sweene, Davrath, Akselrod, 2005; Kotani, Hidaka, Yamamoto, 2000). RSA is an integral part of the parasympathetic nervous system: the branch of the autonomic nervous system that is involved in relaxation, and *modulation* of coping responses, thus contributing to the body's homeostasis. People with active parasympathetic nervous systems (and high-amplitudes of RSA) tend to be healthier, younger, and in better aerobic condition than others (Bernston, et al., 1997) reflecting a stronger self-regulatory function. Note that this description of RSA overlaps the description of HF HRV described above (Section 1.4.1.2). In normal resting adults, RSA usually occurs in the HF range, so HF HRV primarily reflects the influences of RSA.

The *pattern* of breathing also plays a role in self-regulation. For example, during conditions of stress, people tend to *sigh* more. One effect of sighing is to increase ventilation, and thus fuel the fight-flight response. Another may be to stimulate the parasympathetic system, and thus stimulate self-regulatory processes (Soltysik & Jelen, 2005). It is known that anxious people tend to sigh more, and thereby increase blood concentrations of CO_2 (Wilhelm, Gerlach, Roth, 2001; Wilhelm, Trabert, Roth, 2001).

It is known that several factors that can be present in the cockpit environment tend to increase ventilation, including high altitude and reduced air pressure (Buhlmann, Spiegel, Straub, 1970; Bernardi, Passino, Wilmerding, 2001; Harding,& Mills, 1983), high levels of atmospheric CO_2 (Papp, Martinez, Klein, Coplan, Gorman, 1995;Stone, Mathur, Keltz, 1978) pollution (Bergau, 1999; Tunnicliffe, O'Hickey, Fletcher, Miles, Burge, Ayres, 1999) and stress (Deitz & Thomas, 1991;Haward, 1968; Wilhelm, Alpers, Meuret, Roth, 2001). Pressure of carbon dioxide concentration in the blood (pCO_2) can fall in stress in healthy people, although this effect is exaggerated among those suffering from anxiety disorders (Wilhelm et al., 2001; Suess, Alexander, Smith, Sweeney, Marion,1980). This represents the potentially dysregulatory response of hypocapnia. However, because pCO_2 is generally much higher (ca. 40 mm Hg) than levels producing symptomatology (usually < 32 mm Hg), small changes in pCO_2 usually have no noticeable behavioral, psychological, or physiological effects, and are part of the body's normal pattern of self-regulation. Severe changes, however, or even small changes from an initially low baseline may trigger hyperventilation symptoms. Although hypocapnia is commonly associated with anxiety, it also can be produced by various metabolic problems, including kidney dysfunction and various dietary problems that might increase acidity of the blood (producing a condition known as "acidosis"). CO_2 contributes to blood acidity, so decreases in pCO_2 , will increase alkalinity. This is sometimes necessary to preserve proper acid:base balance. However pronounced decreases in pCO_2, usually defined as levels < 32 mm Hg, and called "hypocapnia," can lead to various uncomfortable body symptoms, as well as a decrease in mental functioning, due to constriction of blood vessels, including those supplying the brain. Hypocapnia can occur during stress and the body's *anticipation* of increased metabolic need, particularly if such changes, produced primarily by increased physical activity, do not actually occur.

The healthy person at rest has a respiratory rate of about 12-16 breaths per minute, and maintains blood levels of carbon dioxide at about 4% (40 mm Hg, or torr). Changes in metabolic need, typically produced by changes in physical and sometimes mental activity, cause reflexive changes in rate and depth of respiration. Sometimes emotional influences and increased arousal levels produce an increase in rate with a decrease in depth, thus equalizing total ventilation, and preserving a constant blood level of carbon dioxide, and, hence, a constant acid: base balance in the blood. During periods of stress and mental or physical effort, over-breathing sometimes occurs, producing hypocapnia and alkylosis (Suess et al.1980). Respiratory pattern changes with an increase in task difficulty (Sammer, 1998; Wientjes, 1992). People breathe more slowly and deeply under mental load (Veltman & Gaillard, 1998). Total ventilation is systematically increased by stress (Suess et al., 1980; Schleifer, Ley, Pan, 1997) by increases in CO2 concentration (Papp, Martinez, Klein, Coplan, 1995; Stone et al., 1978) by presence of air pollution (Bergau, 1999; Tunnicliffe et al., 1999; Lindgren & Norback, 2002) low relative humidity (Nagda, 2001) and by decreases in air pressure (Buhlmann, Spiegel, Straub, 1970; Bernardi, Passino, Wilmerding, 2001). These conditions may each exist at times in the cockpit, and may co-occur, and could lead to hypocapnia in otherwise healthy and nonanxious individuals (Gibson, 1984; Butler, Nicholas, Lackland, Friedberg, 2000; Cherniak, Lavietes, Tiersky, Natelson, 2001; Lim & Koh, 2003; Maresh, Armstrong, Kavouros, 1997; Bohnker, Fraser, Baggett, Hayes, 1991). There is considerable evidence of changes in ventilation in airplane pilots, related to workload and stress (Casali & Wierwille, 1984; Wilson, 1993; Lindholm & Sisson, 1985). The current study assessed both mechanical respiratory activity (volume and frequency of ventilation, inspiratory flow rate, etc.) and end-tidal CO_2 (ETCO2) which correlates highly with CO_2 pressure in the blood (pCO_2) (Takano, Sakamoto, Kiyofuji, Ito, 2003; Prause, Hetz, Lauda, Pojer, Smolle-Juettner, Smolle, 1997).

Respiration rate also can systematically affect HRV. For example respiratory sinus arrhythmia is systematically attenuated during faster respiration, independently of vagus nerve activity (Eckerg & Eckberg, 1982; Song & Lehrer, 2003). Additionally, when respiration slows to below 0.15 Hz, LF HRV systematically increases and HF HRV decreases because respiratory sinus arrhythmia is now reflected in LF HRV rather than, as is more usual, in HF HRV. Slow breathing often occurs after periods of high workload (e.g. after landing) (Jorno, 1993).

Thus, we had two purposes in measuring respiration:
1. To assess the degree to which various respiratory parameters reflect task difficulty.
2. To detect incidences of hypocapnia.

1.4.3. Eyeblink activity

Eyeblink activity has been employed for over sixty years in the investigation of mental activities. The rate of blinking has, in general, been found to decrease when performing tasks requiring visual scanning (Iwanaga, Saito, Shimomura, Harada, Katsuura, 2000; Tanaka, 1999; Skotte, Nojgaard, Jorgensen, Christensen, Sjogaard, 2007; Wilson, Fullenkamp, Davis, 1994) and sometimes in nonvisual tasks as well (Gregory, 1952). Although it is not reliably affected by task difficulty (Cho, Sheng, Chan, Lee, Tam, 2000), there are reports of a positive association with blink rate (Drew, 1951; Tanaka & Yamaoka, 1993). Blink rate tends to increase during conversation, compared with rest (Bentivoglio, Bressman, Cassetta, Carretta, Tonali, Albanese, 1997) and decrease in fatigue (Barbata, De Padova, Paolillo, Arpaia, Russo, Ficca, 2007; Caffier, Erdmann, Ullsperger, 2003; Caffier, Erdmann, Ullsperger, 2005; Ingre, Akerstedt, Peters, Anund, Kecklund, 2006; Stern, Boyer, Schroeder, 1994). Blink rate is elevated during periods of task-induced arousal (Tanaka, 1999) and among psychiatric patients (Swarztrauber & Fujikawa, 1998), notably those with depression (Mackintosh, Kumar, Kitamura, 1983), panic disorder (Kojima, Shioiri, Hosoki, Sakai, Bando, Someya, 2002) and schizophrenia (Mackert, Flechtner, Woyth, Frick, 1991; Mackert, Woyth, Flechtner, Voltz, 1990). There also is particular evidence that eye-blink rate is inversely related to visual processing and visuomotor attention (Weiner & Concepcion, 1975). In airplane pilots, closure duration is lower in actual than simulated flights (Wilson, Fullenkamp, Davis, 1994), decreases in multitask situations relative to single task environments, (Sirevaag, Kramer, Coles, & Donchin, 1989) and increases with time in task, presumably due to increases in operator fatigue (Wilson, 2002). In the present study measures of blink rate and blink duration were used to assess changes in participants' workload.

1.4.4. Dysfunctional physiological responses that may increase flight risk.

1.4.4.1. Hypocapnia

Hypocapnia is known to reduce brain blood flow (Hida, Kikuchi, Okabe, Miki, Kurosawa, Shirato, 1996; Bednarczyk, Rutherford, Leisure, Munger, Panacek, Miraldi, Green, 1990) and to impair performance on various psychomotor tasks (Van Deist, Stegen, Van de Woestijne, Schippers, Van den Bergh, 2000; Gibson, 1978). Other symptoms of hypocapnia include dizziness and chest pain (Brown & Barlow, 1997; Fried, 1987). There has been speculation that impaired judgment caused by hypocapnia may have contributed to several air disasters (Gibson, 1984; Carley, 1999). We have surveyed civilian airline pilots through an industry newsletter, and, of 55 pilots returning questionnaires, three reported having experienced clinically significant in-flight hyperventilation symptoms. Presumably any task that can produce hypocapnia in a healthy pilot should not be part of routine flight procedures. Our purpose was to determine whether hypocapnia can be induced by high task-load tasks in a flight simulator. Studies of in-flight hyperventilation symptoms probably underestimate the problem because aircrew members do not readily endorse such symptoms, for fear of losing credibility with co-workers and potential job loss.

1.4.4.2. Hypertensive reactions

Very high levels of blood pressure and heart rate induced by acute stress can produce an immediate health risk, and, in rare cases, can even lead to a cardiac or cerebro-vascular event (Myers,& Dewar, 1975; Chockalingam, Venkatesan, Dorairajan, Moorthy, Chockalingam, Subramaniam, 2003). This can occur even in some apparently healthy individuals (Bensyl, Moran, Conway, 2001). Stress-induced cerebro-vascular events leading to airplane crashes have been documented even among young and apparently healthy fliers (Bensyl et al, 2001)

1.5. Aims of this study

In this preliminary study of seven individuals our aims were as follows:

1.5.1. To determine whether physiological measures can be reliably taken in standardized flight simulator tasks
1.5.2. To determine the relationship between physiological response and both flight difficulty and performance ratings
1.5.3. To determine whether physiological measures add detectability of task load and predictability of pilot performance over that provided from a commonly used self-report measure of workload [the National Aeronautics and Space Administration-Task Load Index (NASA-TLX)](Hart & Staveland, 1988) when used alone (i.e., without adding physiological data to the prediction model)
1.5.4. To determine whether potentially unsafe levels of physiological arousal may occasionally occur in any individual subject during difficult flight maneuvers in the flight simulator situation.
1.5.5. To assess a psychological trait that is often related to underreport of subjective stress and to exaggerated physiological response, and to determine whether these relationships are present among pilots tested in a flight simulator.

2. RECORDING PROCEDURES

2.1. Equipment

We tested subjects in a Boeing 737B flight-800 Level D flight simulator located in the FAA Mike Monroney Aeronautical Center, Oklahoma City. During the simulator evaluation, participants were asked to wear the LifeShirt Garment (VivoMetrics, CA, USA) − a non-invasive, lightweight (8 oz.), comfortable and easy-to-use nylon shirt. Pulmonary function was monitored via sensors around the subject's chest and abdomen. A single-channel ECG measured cardiac function, and a dual-axis accelerometer recorded subject posture and body movement. Additional peripheral devices measured the electro-oculogram (EOG) in order to assess eyeblinks, and $ETCO_2$.

The LifeShirt has not previously been used for evaluating flight tasks. We therefore developed a manual for using it in the flight simulator (see Appendix).

Blood pressure was taken from the nondominant arm within a minute after each task, using an Omron Automatic Blood Pressure Monitor with IntelliSense ™ Model HEM-705CP.

Mechanical respiration data were collected using inductance plethysmography (Hill et al, 1982), which measures chest and abdominal wall movement. It consists of a pair of insulated coils sewn into a nylon vest, positioned over the chest and upper abdomen. The change in mean cross-section area of the coil caused by chest and abdominal wall displacement modifies the inductance of the coil. The apparatus was calibrated from three breaths into an 800 ml bag. This device has been validated for assessment of tidal volume, respiration rate (Bloch, Burundian, Sackner 1995; Cantineau, Escourrou, Sartene, Gaultier, & Goldman, 1992; Cohen, et al, 1997; Gonzalez, Haller, Watson, & Sackner, 1984; Leino, Nunes, Valta, & Takala, 2001). It also provides measures of respiratory flow that correlate highly with those obtained by spirometry (Hill, Blackburn, & Williams, 1982; Hudgel, Capehart, Johnson, Hill, &Robertson, 1984), and from which minute volume ventilation was derived.

$ETCO_2$ was collected from a VitalCap Capnograph (Oridion, MA, USA) via a nasal/oral canula. The sensor collected exhaled air from both the nose (through a canula) and from a small tube to the mouth. Scoring of $ETCO_2$ can be tricky, because incomplete breaths can produce spuriously low readings. Complete breaths show a characteristic shape, however, so a skilled observer can easily identify them. To make the scoring process easier, we looked for a cut-off high-pass criterion, such that almost all values lower than the cut-off reflected incomplete breaths and all values above it reflected complete breaths. We set a cut-off for each individual, where lower $ETCO_2$ values represented incomplete breaths and higher ones complete breaths, and eliminated values below the cut-off in all analyses. The motion detector was taken from a crystal component. Motion was subsequently determined by subtracting a postural component from the raw signal, removing all DC offsets related to posture. The residual was then rectified to report the (RMS) root mean square value of the motion signal. Accelerometer data were then sampled at 10 Hz. The signal can range from 1-100 (arbitrary units). Supporting documentation with this equipment reports that, when in the supine resting position, the mean generally is below 5. When in the supine position and moving, the signal can reach 10-15 in amplitude. Walking slowly produces approximately 2-5 units. Walking at a medium pace produces 7-10 units. Walking quickly produces a range of approximately 12-18 arbitrary units.

2.2. Study participants

Eight male professional pilots were recruited for the study, which was designed as a preliminary feasibility study for psychophysiological assessment in the flight simulator. Seven of the pilots were full time volunteer employees of the FAA Mike Monroney Aeronautical Center, and one was a volunteer research collaborator who was a commercial airline pilot. Participant characteristics are summarized in Table 2.

Participants were informed that the experiment concerns testing the suitability of physiological measurements for measuring workload. We also queried subjects about their expertise levels, both in terms of flying experience and familiarity with the Boeing 737 environment.

Table 2. Demographic information

Subject ID	Age	Flight experience	Medication	Other
000	35	13	No	5’10”, 180 lbs
001	44	23	No	5’9” 165
002	49	33	indapamide (5mg/day)	5’10” 185lbs
003	52	30	atorvastatin calcium, Aspirin	-
004	55	35		PVC’s, aborted
005	61	38	No	Untreated hypertension
006	61	36	No	-
007	39	20	No	Abnormal EKG

- All subjects were Caucasian males. Except for one subject (000) all had had initial flight experience in the military.
- Subjects 000 and 007 were non-FAA test pilots. One was an active commercial airlines pilot, although not certified to fly a 737B aircraft. The other was on furlough, and currently working for the U.S. Air Force.
- Subject 004 was aborted because he manifested frequent preventricular contractions, which interfered with recording of HRV variables.

2.3. Procedures

Research procedures were approved by the Institutional Review Board of the University of Medicine and Dentistry of New Jersey. Following verbal and written informed consent, the physiological monitoring equipment was attached. Following this, the following tasks were administered, in a single session, each task lasting for approximately five minutes.

We first presented two tasks to evaluate baseline physiology and reactivity: a standardized “plain vanilla” baseline, with minimal stimulation designed to keep subjects awake and focused on a standard task; a task involving breathing six times per minute, in order to evaluate baseline physiological responsivity to a standard physiological stimulus that sensitively activates both physiological reactivity to external stimulation and the body’s modulatory responses to such reactions. We also presented subjects with a mental arithmetic task (serially subtracting 7 from 1000, performed out loud) in order to assess physiological response to a mild nonflight mental stressor.

We then presented 18 standard flight tasks, as described in Table 1. Difficulty level of each was determined by senior staff of the FAA Mike Monroney Aeronautical Center.

Afterward, we presented a maximally stressful flight task, with multiple severe problems occurring simultaneously, in order to measure maximal physiological response in response to flight simulator tasks. To determine the interaction among flight task difficulty and internal body rhythms at about 6/min, we also presented a series of relatively easy flight tasks at a rate of 10 sec.

We evaluated the reliability and validity of measures in two ways: 1) by examining records to determine whether various flight task behaviors produced artifact in the physiological recordings, and 2) by examining the relationship between physiological arousal and flight task difficulty. Where there was a marked discrepancy, we searched for possible reasons for this (including mislabeling of difficulty level and measurement artifacts inherent in the situation).

We also determined the optimal position for placing sensors. EKG sensors were placed at the midpoint of the side of the rib cage, which produced minimal artifact during flight tasks. Other sensors as described in the Vivometrics manual.[1] We also determined and tested reliability of data transmission in the simulator environment, pilot comfort, and noninterference with aviator tasks in the simulator. Feedback from pilots was obtained during various tasks, to help in refining procedures and interpreting data. Electro-occulogram data were collected from three surface EMG electrodes placed 1) on the forehead 2 cm above the bridge of the nose, 2) as close as possible to the right of the right eye socket, and 3) behind the right ear.

We also performed a number of analyses in order to determine a method for quantifying each physiological variable in order to maximize sensitivity to flight task difficulty, as described below.

2.3.1. PHYSIOLOGICAL MEASURES

2.3.1.1. Heart Rate (HR)

2.3.1.2. Heart Rate Variability (HRV)

We computed HF, LF, and VLF HRV as described above. We also computed the LF; HF ratio, which is often used to assess sympathetic: parasympathetic balance.

2.3.1.3. Blood pressure

Blood pressure was taken by a research assistant from the nondominant arm within a minute of the end of each task. For four subjects (5,6,7, and 8) we also took blood pressure measures immediately before the initiation of each task. The cuff remained deflated, but attached to the subject, throughout each of the tasks.

2.3.1.4. Respiration

We examined the following respiratory patterns:

1. Respiratory rate
2. Minute volume ventilation (the volume of air breathed each minute)
3. Frequency of sighs (a measure that is related to anxiety)
4. $ETCO_2$. Note: we had these data on only four subjects.
5. Various measures of respiratory drive, usually associated with force or speed of inhalation

2.3.1.5. Electro-oculographic activity (EOG)

We had these data on four of the seven subjects.

2.3.1.6. Motion detector

A motion sensor embedded in the LifeShirt[2] produced an electrical signal each time the person moved, or made a postural change. This provided an electrical output that could be quantified and integrated, thus yielding an index of physical motion. Under ordinary circumstances, the motion detector is primarily influenced by muscular activity. During states of stress and tension, people tend to have more muscular activity (Nilsen, Sand, Stovner, Leistad , Westgaard, 2007) , which often is seen as "fidgeting" so the motion detector could be called a "fidgetometer." However recordings also could be influenced by movement of the flight simulator, which, in our situation, would represent artifact. Such artifact can be useful, however, in explaining anomalies in other measures.

2.3.2. Description of flight tasks

The scenarios are grouped in three flight phases: Takeoff, In-flight (climb, cruise, descent), and Approach & Landing. The first run in each phase would be the baseline run, i.e. normal operations. Following that, four or five runs in each phase averaging approximately 6-7 minutes a run would result in a total activity time of 90 to 110 minutes in a two hour period allowing approximately 10 to 15 minutes for repeats, debriefing and reset time. Tasks were all presented in the same order, as listed below.

Task difficulty (high [H], medium or moderate [M], low [L]) was determined by FAA staff, and was treated by us as an *a priori* independent variable.

Table 3. Flight Tasks

Takeoff Phase:

T1. Normal takeoff and departure to 5000' (Baseline)
T2. Takeoff with engine fire just after getting airborne (preset 20-30' for the fire) or just after entering the weather (100') (M)
T3. Takeoff into a moderate to severe wind shear (H)
T4. Takeoff into a 600 RVR (no HUD) (L)
T5. Lightweight takeoff with engine separation just after getting airborne (preset 20-30' for the failure) (M)
T6. Loss of brakes on taxi from gate to takeoff position (M)

In-flight Phase:

F1. Normal climb and acceleration from 8000' to 13000', or normal descent and deceleration from 13000' to 8000' (Baseline)
F2. Descent from 10000' with severe wake turbulence resulting in a nose-low upset starting at 8000' (disable flight freeze for entry) (H)
F3. Rapid depressurization ~at 35000' (H)
F4. Weather front system penetration (thunderstorms) at 25000' (L)
F5. TCAS RA (near-miss) at 10000' (M)

Approach & Landing Phase

L1. Normal visual landing from 6NM (Baseline)
L2. ILS to a landing in an 1800 RVR (no HUD) (L)
L3. Manual reversion or elevator quadrant jam landing (H)
L4. Landing into a moderate to severe wind-shear (M)
L5. Low altitude severe wake turbulence encounter (200') during approach (H)

L6. Landing with one main gear stuck up (H)
L7. Terrain avoidance warning on the ground (i.e., pull up, pull up) (M)

2.3.3. Self-report of task load: NASA's TLX scale.

This measure was taken immediately after each flight task.

2.3.3. Evaluator scores

We used a 5-point scale for evaluating pilot performance (see Table 4). Evaluation was done by an experienced test and check pilot, who also programmed the various tasks on the flight simulator. Higher scores reflected better performance on the task. There were no standardized criteria used for the scoring, but the following characteristics contributed to the ratings: successful completion of task (no crashes), maintenance of heading, altitude, and approach into handling emergency (timing, etc.). This was a subjective rating given by a senior check pilot who was very experienced in evaluating pilots in the simulator environment. Pilots were rated after each consecutive task. They were not provided with feedback from the evaluator until completion of the test series.

Table 4. Evaluator Score Ratings

0	Failed task/ crash
1	Poor
2	Adequate
3	Good
4	Excellent
5	Outstanding

3. RESULTS: PHYSIOLOGICAL DISCRIMINATION AMONG LEVELS OF *A PRIORI* LOAD AMONG FLIGHT TASKS, AND CHOICE OF PHYSIOLOGICAL MEASURES AND FLIGHT TASKS FOR FURTHER RESEARCH.

3.1. Elimination of tasks

Below we present graphs both for all tasks given to participants in this study and for tasks selected for future research, and we indicate differences between levels of *a priori* ratings of task load. Probability levels for differences between loads are reported, although they must be considered tentative because of the small *n* in this research. In some cases, differentiation among levels of task load was greatest for landing tasks, because the range of physiological response to tasks was greatest for these tasks (i.e., takeoff and landing tasks uniformly produced smaller physiological demand). In selecting tasks for future research, we eliminated tasks for the following reasons: 1) the tasks presented recording difficulties or produced artifact in the recordings, 2) the tasks provided information that duplicated that provided by other tasks, and 3) the tasks gave physiological and/or self report results that were discrepant from the *a priori* ratings of task load.

3.1.1. *Recording difficulties*

3.1.1.1. We eliminate F3 (Rapid depressurization ~at 35000' --- high demand) because pilots reported that it was unrealistic, since they could not use oxygen masks, which would interfere with CO_2 sensors on the face. If this task were considered to be critical, sensors would need redesigning (e.g., attaching them more firmly, including additional sensors in the oxygen mask, etc.) to allow use of a mask. This task produced the lowest blood pressure and heart rate readings and highest high-frequency HRV of all high-demand tasks. This suggests that subjects were responding physiologically to the task as if it were closer to low task demand than high, despite TLX ratings of the task as high-demand. It appeared as if, physiologically, they were not ”engaged” with this task.

3.1.1.2. We eliminate F4 [Weather front system penetration (thunderstorms) at 25000', rated as Low Demand] because it yielded respiratory and movement data showing more extreme arousal than most of the High Demand tasks. We believe that this may have been an artifact of vibrations in the simulator that produced some spurious readings. Heart rate was as low as in most Low Demand tasks, which would be anomalous for a task producing increased muscular activity and ventilation. To be certain, we would have to check this hypothesis by attaching sensors to a passenger in the simulator during this task. Another possibility is that the task is, in fact, not Low Demand. Subjects rated it as equivalent to Medium Demand tasks on the TLX. Note that $ETCO_2$ was exceptionally low during this task and indices of respiration high. We interpreted this as due to movement of the sensors and spurious readings. Such inconsistencies lower our confidence in interpreting the physiological data for this task.

3.1.2. *Redundancy*

We eliminate T4 [Takeoff into a 600 RVR (no HUD), Low Demand] because physiological data were very similar to T1 (normal takeoff), although the item was rated close to “medium load” on the TLX; and L2 [ILS to a landing in an 1800 RVR (no HUD)] because data were very similar to L1 (normal landing).

3.1.3. *Inconsistency of response with ratings.*

3.1.3.1. We eliminate L5 [Low altitude severe wake turbulence encounter (200') during approach, High Demand] because data were more similar to Medium Demand tasks than to High Demand, on the TLX, $ETCO_{2,}$ heart rate, and high frequency HRV.

3.1.3.2. We eliminate L7 (Terrain avoidance, Medium Demand) because it yielded responses similar to L4 (Landing into a moderate to severe wind shear, rated as Medium demand) on some measures (e.g., TLX, HF HRV), but with lower levels of arousal on other measures ($ETCO_2$, heart rate blood pressure). Although such an inconsistency might be of interest for further study, the inconsistency may add noise to a predictive psychophysiological measure of task demand.

4. Statistical model

Use of probability statistics with such a small number of subjects has major limitations, due to lack of power. Thus borderline significant findings are reported as well as significant ones. In an exploratory study with a large number of repeated observations on many variables, probability analyses can provide guidance for future research. They are presented here with this purpose in mind, not as definitive statements of significance or, especially, nonsignificance of findings.

In order to assure that our findings of significance in “selected tasks” are not due to selective choice of flight tasks showing good discrimination, we first analyzed data from all flight tasks. A random effects logistic regression model was applied for each physiological variable, to test if any of the physiological variables is a significant detector for *a priori* load level (low vs. high and low vs. medium). In later analyses, we also adjusted for the NASA TLX Total score, in order to test incremental effectiveness of physiological measures after a cheaper and simpler method was applied. We then repeated these computations and performed more detailed analyses with data limited to the tasks we have chosen for future research. These include: Low demand tasks T1, F1, L1, L2; medium demand tasks T2, T6, F5, L4; and High demand tasks T3, F2, L3, and L6. We note here that detection of task load tends to be smaller for individual TLX scales than for total TLX score. We later show that adding physiological variables to TLX values increases detectability. Because of the small number of subjects, we did not attempt to construct a physiological index, which may lend greater sensitivity to task load differences than individual measures.

We also tested whether any of the differences from baseline were significant predictors for Evaluator Score, after NASA Total score (TLX-total) was added to the model. “Baseline” was assessed, separately, in three ways: The first baseline reference was the vanilla task, which assessed resting levels of physiological activity). The second baseline analysis defined baseline as the pre-flight-task 0.1 Hz breathing period. This controls for the body’s constitutional reaction to stimulation, including components of both an initial reaction to adapt the body to the effect of a stimulus (in this case, breathing) as well as the strength of a homeostatic reaction, mediated by the baroreflex system, whereby blood pressure and other cardiovascular responses are modulated by homeostatic processes (Vaschillo, Vaschillo, & Lehrer, 2006). We also used the mental arithmetic task as a control involving mild mental effort, with little of the physical involvement or stress involved in the flight tasks.

For each variable, we controlled for baseline data in two ways: by analyzing deviation from baseline scores (thus controlling each individual score for baseline effects), and by including baseline scores as a covariate (thus controlling mean subject values across tasks for baseline effects). Adding the baseline scores to the model determined whether change in physiological measures (from baseline) was baseline dependent, thus requiring a baseline control in future studies. This analysis was done only on tasks chosen for future research. As outline below, the ability of physiological measures to detect task difficulty and to predict pilot performance was enhanced by including baseline values.

We evaluated detection of *a priori* flight task detection using a mixed model analysis with regression coefficients and p-values, with and without controlling for TLX values. We also computed the C-statistic.[3] The C-statistic is the area under the receiver operating characteristic (ROC) curve. It can be used to assess the accuracy of a test, that is, how well the test differentiates between groups. In our study, we used C-statistics to assess how well the physiological measurements can differentiate the *a priori* task load levels (High vs. combined Medium and Low-load, and High vs. Medium load), and how much more accuracy the physiological measurements can add to the single use of TLX Total in differentiating task load levels.

Performance evaluator scores were analyzed using a mixed model analysis. We evaluated the association between physiological measures with and without TLX (and/or with and without AccM), by the regression coefficients and p-values. We also assessed the predictibility of a statistical model using Akaike’s Information Criterion (AIC, Akaike, 1973) based on the values of the maximized log likelihood and the number of parameters in the statistical model. AIC is well known as a commonly used information measure to assess the closeness of the outcomes estimated by a statistical model to the actually observed outcomes. Among all competing models, the one with smallest AIC is considered the best model, as long as the difference is at least 1.0. However, the absolute AIC value is not meaningful. We

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[3] The value of the C-statistic of 1 represents a perfect test; an area of .5 represents a worthless test. A general guide for classifying the accuracy of a diagnostic test is the traditional academic point system:
.90-1 = excellent (A)
.80-.90 = good (B)
.70-.80 = fair (C)
.60-.70 = poor (D)
.50-.60 = fail (F)

used the AIC to measure the predictability of a statistical models by viewing it as a measure of the closeness between the predicted outcomes of a statistical model to the actually observed outcomes, and compare the values between models using physiological variables, with and without TLX to assess the contribution of physiological variables over TLX measures.

5. Summary of results

This paragraph summarizes results presented below. Although individual physiological variables alone tended to be only fair to poor discriminators of *a* priori ratings of flight task loads, when combined with the TLX some cardiac measures and gross body movement both added significant ability for task load discrimination over the TLX alone. They similarly added significant ability to predict pilot performance, as assessed by evaluator scores, over the TLX alone. Additionally, evidence was found that simulator tasks can evoke both hypocapnia and very high blood pressures, at levels that could pose potential safety risks.

6. Detection of *a priori* flight task load from psychophysiological measures.

In this section we describe the ability of physiological measures to detect differences among levels of flight task load, as rated *a priori* by FAA staff, without adjusting for baseline, and without considering TLX effects. Because detecting tasks with high load from those with lesser load would be important for policy decisions about the safety of various flight tasks, for each physiological variable, we computed comparisons between *a priori* high load tasks and either 1) combined low- and medium-load tasks or 3) medium load tasks alone, using both all tasks and for tasks selected for future research. Although the former analysis has more power, it also probably includes more noise than the latter. Given the exploratory nature and low power of this study, we include both of these analyses (Tables 5-8).

Table 5a. Discriminating High load from combined Medium and Low load tasks using Physiological Measures Alone: all tasks, no baseline adjustment

Effect	Regression Coefficient	Standard Error	*df*	*t*	*p*	C-statistic
CARDIAC MEASURES						
Mean RRI	-0.0019	0.0016	110	-1.2209	0.2247	0.5879
SD RRI (SDNN)	0.0127	0.0062	110	2.0208	0.0457	0.6117
Min RRI/task	-0.0127	0.0032	110	-3.9166	0.0002	0.7331
Mean HR	0.0299	0.0187	110	1.6042	0.1116	0.5997
LF HRV	2.09E-05	0.0001	110	0.1828	0.8553	0.5185
HF HRV	9.53E-06	0.0005	110	0.0191	0.9848	0.5087
log LF HRV	-0.0094	0.1227	110	-0.0766	0.9391	0.5300
log HF HRV	-0.0464	0.1211	110	-0.3830	0.7024	0.5397
log VLF HRV	0.0833	0.1748	110	0.4764	0.6347	0.5273
LF:HF HRV ratio	0.0001	0.0006	110	0.2221	0.8247	0.5660
Normalized HF HRV	-3.6803	2.8826	110	-1.2767	0.2044	0.5647
Normalized LF HRV	3.5177	2.7538	110	1.2774	0.2041	0.5693
Ventric. systole time	-0.0023	0.0041	111	-0.5599	0.5767	0.5211
Ventric. relax. Time	-0.0245	0.0162	111	-1.5164	0.1323	0.5516
Heart muscle condt'n	0.3483	0.2537	111	1.3729	0.1726	0.5407
Cardiac economics	0.0389	0.0469	111	0.8304	0.4081	0.5423
Ventric relax % RRI	-0.0986	0.1238	111	-0.7960	0.4277	0.5080
Systole % RRI	0.0701	0.0611	111	1.1464	0.2541	0.5557
BLOOD PRESSURE MEASURES						
SYSTOLIC BP	0.0131	0.0093	113	1.4085	0.1617	0.5624
DIASTOLIC BP	-0.0092	0.0163	113	-0.5625	0.5749	0.5466
RESPIRATION MEASURES						
Respiration Rate	0.0372	0.0471	110	0.7885	0.4321	0.5710
MIN VOL VENTIL	0.0619	0.0343	110	1.8072	0.0735	0.5871
Mean ETCO2/task	-0.0520	0.0701	110	-0.7413	0.4601	0.5641
Min ETCO2/task	-0.0339	0.0509	110	-0.6656	0.5071	0.5506
% Sighs	0.0005	0.0292	110	0.0160	0.9872	0.5524
BODY MOVEMENT						
Movement	1.5670	1.0639	110	1.4730	0.1436	0.6773

Note –For definitions of variables "ventric.systole time"– "Systole %RRI"" see table 9. They refer to measures of heart function, as determined from the shape of the EKG wave. Differences among measures in df result from equipment failure.

Table 5b. Discriminating High load from Medium load tasks using Physiological Measures Alone: all tasks, no baseline adjustment

Effect	Regression Coefficient	Standard Error	*df*	*t*	*p*	C-statistic
CARDIAC MEASURES						
Mean RRI	-0.0008	0.0018	71	-0.4575	0.6487	0.5380
SD RRI (SDNN)	0.0127	0.0073	71	1.7337	0.0873	0.6170
Min RRI/task	-0.0050	0.0025	71	-1.9788	0.0517	0.6469
Mean HR	0.0152	0.0206	71	0.7381	0.4629	0.5499
LF HRV	0.0000	0.0001	71	0.2150	0.8304	0.5375
HF HRV	0.0002	0.0006	71	0.3988	0.6913	0.5258
log LF HRV	0.0263	0.1450	71	0.1817	0.8564	0.5375
log HF HRV	-0.0180	0.1437	71	-0.1254	0.9006	0.5235
log VLF HRV	0.1578	0.1975	71	0.7991	0.4269	0.5485
LF:HF HRV ratio	0.0000	0.0007	71	0.0227	0.9819	0.5752
Normalized HF HRV	-4.2146	3.2332	71	-1.3035	0.1966	0.5752
Normalized LF HRV	3.8200	3.1203	71	1.2242	0.2249	0.5740
Ventric. systole time	-0.0011	0.0047	72	-0.2364	0.8138	0.5009
Ventric. relax. Time	-0.0232	0.0176	72	-1.3132	0.1933	0.5502
Heart muscle condt'n	0.3046	0.2904	72	1.0490	0.2977	0.5401
Cardiac economics	0.0081	0.0533	72	0.1515	0.8800	0.5000
Ventric relax % RRI	-0.1600	0.1384	72	-1.1561	0.2515	0.5555
Systole % RRI	0.0276	0.0698	72	0.3959	0.6934	0.5075
BLOOD PRESSURE MEASURES						
SYSTOLIC BP	0.009648	0.010572	73	0.9126	0.364457	0.544715
DIASTOLIC BP	-0.0068	0.01838	73	-0.37	0.712452	0.543554
RESPIRATION MEASURES						
Respiration Rate	0.0500	0.0597	71	0.8374	0.4052	0.5700
Minute vol ventil	0.0426	0.0389	71	1.0947	0.2773	0.5624
Mean ETCO2/task	-0.0246	0.0779	71	-0.3165	0.7525	0.5514
Min ETCO2/task	0.0121	0.0551	71	0.2190	0.8273	0.5334
% Sighs	0.0190	0.0362	71	0.5261	0.6005	0.5862
BODY MOVEMENT						
Movement	5.5298	2.1014	71	2.6314	0.0104	0.6850

Table 5c. Discriminating High load from combined Medium and Low load tasks using Physiological Measures Alone: tasks selected for future research, no baseline adjustment

Effect	Regression Coefficient	Standard Error	*df*	*t*	*p*	C-statistic
CARDIAC MEASURES						
Mean RRI	-0.0030	0.0020	71	-1.4996	0.1381	0.6563
SD RRI (SDNN)	0.0127	0.0075	71	1.6879	0.0958	0.6311
Min RRI/task	-0.0136	0.0038	71	-3.5849	0.0006	0.8045
Mean HR	0.0450	0.0233	71	1.9319	0.0574	0.6709
LF HRV	-1.6E-05	0.0001	71	-0.1221	0.9031	0.5689
HF HRV	-0.0003	0.0006	71	-0.4548	0.6506	0.5871
log LF HRV	-0.0626	0.1477	71	-0.4240	0.6728	0.5689
log HF HRV	-0.1157	0.1477	71	-0.7834	0.4360	0.5871
log VLF HRV	-0.0491	0.2045	71	-0.2402	0.8109	0.5950
LF:HF HRV ratio	0.0003	0.0007	71	0.4070	0.6852	0.6193
Normalized HF HRV	-5.0406	3.7553	71	-1.3422	0.1838	0.6199
Normalized LF HRV	4.5809	3.5425	71	1.2931	0.2002	0.6119
Ventric. systole time	-0.0033	0.0049	72	-0.6774	0.5004	0.5418
Ventric. relax. Time	-0.0236	0.0192	72	-1.2280	0.2234	0.5507
Heart muscle condt'n	0.3086	0.3547	72	0.8698	0.3873	0.5274
Cardiac economics	0.0687	0.0587	72	1.1708	0.2456	0.5800
Ventric relax % RRI	-0.0536	0.1556	72	-0.3446	0.7314	0.4876
Systole % RRI	0.1007	0.0743	72	1.3550	0.1797	0.5893
BLOOD PRESSURE MEASURES						
SYSTOLIC BP	0.019601	0.010904	74	1.797555	0.076327	0.620217
DIASTOLIC BP	-0.0047	0.018435	74	-0.25475	0.799623	0.545281
RESPIRATION MEASURES						
Respiration Rate	0.1428	0.0636	71	2.2456	0.0278	0.6808
Minute vol ventil	0.0967	0.0434	71	2.2284	0.0290	0.6556
Mean ETCO2/task	-0.0750	0.0809	71	-0.9277	0.3567	0.6004
Min ETCO2/task	-0.0754	0.0608	71	-1.2398	0.2191	0.6161
% Sighs	0.0057	0.0354	71	0.1624	0.8715	0.5832
BODY MOVEMENT						
Movement	8.1796	2.3663	71	3.4568	0.0009	0.7860

Table 5d. Discriminating High load from Medium load tasks using Physiological Measures Alone: tasks selected for future research, no baseline adjustment

Effect	Regression Coefficient	Standard Error	*df*	*t*	*p*	C-statistic
CARDIAC MEASURES						
Mean RRI	-0.0017	0.0021	45	-0.7963	0.4301	0.6110
SD RRI (SDNN)	0.0122	0.0087	45	1.4002	0.1683	0.6403
Min RRI/task	-0.0068	0.0032	45	-2.0842	0.0428	0.7385
Mean HR	0.0279	0.0249	45	1.1214	0.2681	0.6244
LF HRV	-2.3E-05	0.0001	45	-0.1615	0.8724	0.5702
HF HRV	-8.7E-05	0.0008	45	-0.1144	0.9095	0.5829
log LF HRV	-0.0430	0.1745	45	-0.2465	0.8064	0.5702
log HF HRV	-0.0956	0.1753	45	-0.5454	0.5882	0.5829
log VLF HRV	0.0311	0.2226	45	0.1399	0.8894	0.5153
LF:HF HRV ratio	4.28E-05	0.0008	45.0000	0.0522	0.9586	0.6301
Normalized HF HRV	-5.0556	4.1566	45	-1.2163	0.2302	0.6301
Normalized LF HRV	4.3941	3.9612	45	1.1093	0.2732	0.6161
Ventric. systole time	-0.0023	0.0055	46	-0.4106	0.6833	0.5185
Ventric. relax. Time	-0.0257	0.0211	46	-1.2184	0.2293	0.5568
Heart muscle condt’n	0.3446	0.4175	46	0.8254	0.4134	0.5357
Cardiac economics	0.0314	0.0672	46	0.4683	0.6418	0.5338
Ventric relax % RRI	-0.1595	0.1779	46	-0.8963	0.3747	0.5364
Systole % RRI	0.0522	0.0827	46	0.6320	0.5305	0.5415
BLOOD PRESSURE MEASURES						
SYSTOLIC BP	0.0167	0.0125	47	1.3277	0.1907	0.6154
DIASTOLIC BP	-0.0033	0.0206	47	-0.1614	0.8725	0.5510
RESPIRATION MEASURES						
Respiration Rate	0.1015	0.0717	45	1.4158	0.1637	0.6639
Minute vol ventil	0.0871	0.0529	45	1.6466	0.1066	0.6480
Mean ETCO2/task	-0.0348	0.0904	45	-0.3849	0.7022	0.5880
Min ETCO2/task	-0.0158	0.0649	45	-0.2435	0.8087	0.5733
% Sighs	0.0681	0.0504	45	1.3520	0.1831	0.6894
BODY MOVEMENT						
Movement	7.1721	2.7700	45	2.5892	0.0129	0.7710

Table 6a. Discriminating High load from combination of Medium- and Low-load tasks using Physiological Measures Alone: all tasks, with baseline adjustment (difference score and baseline as covariate): VANILLA BASELINE

Effect	Regression Coefficient	Standard Error	*df*	*t*	*p*	C-statistic
CARDIAC MEASURES						
Mean RRI	-0.0058	0.0027	110	-2.1221	0.0361	0.5997
SD RRI (SDNN)	0.0226	0.0085	110	2.6596	0.0090	0.6614
Min RRI/task	-0.0142	0.0036	110	-3.9593	0.0001	0.7190
Mean HR	0.0648	0.0283	110	2.2855	0.0242	0.6208
LF HRV	0.0000	0.0001	110	0.3568	0.7219	0.5460
HF HRV	0.0004	0.0009	110	0.4361	0.6636	0.5445
log LF HRV	0.0475	0.1951	110	0.2436	0.8080	0.5389
log HF HRV	-0.0642	0.2625	110	-0.2446	0.8072	0.5430
log VLF HRV	0.1772	0.2195	110	0.8073	0.4212	0.5339
LF:HF HRV ratio	0.0002	0.0006	110	0.2410	0.8100	0.5499
Normalized HF HRV	-4.1129	3.0203	110	-1.3618	0.1761	0.5691
Normalized LF HRV	4.0875	2.9427	110	1.3890	0.1676	0.5690
Ventric. systole time	-0.0076	0.0068	111	-1.1208	0.2648	0.5476
Ventric. relax. Time	-0.0216	0.0147	111	-1.4676	0.1451	0.5244
Heart muscle condt’n	0.4017	0.2842	111	1.4137	0.1603	0.5465
Cardiac economics	0.0828	0.0740	111	1.1194	0.2654	0.5610
Ventric relax % RRI	-0.1482	0.1521	111	-0.9743	0.3320	0.5037
Systole % RRI	0.1535	0.0955	111	1.6077	0.1108	0.5654
BLOOD PRESSURE MEASURES						
SYSTOLIC BP	0.0333	0.0166	113	2.0054	0.0473	0.5938
DIASTOLIC BP	-0.0181	0.0202	113	-0.8964	0.3719	0.5463
RESPIRATION MEASURES						
Respiration Rate	0.0580	0.0561	93	1.0343	0.3037	0.5815
Minute vol ventil	0.0637	0.0357	93	1.7826	0.0779	0.5750
Mean ETCO2/task	-0.2304	0.1663	93	-1.3850	0.1694	0.5882
Min ETCO2/task	-0.0365	0.0665	93	-0.5483	0.5848	0.5458
% Sighs	0.0160	0.0322	93	0.4967	0.6206	0.5521
BODY MOVEMENT						
Movement	2.5390	1.3353	93	1.9015	0.0603	0.6450

Table 6b. Discriminating High load from Medium load tasks using Physiological Measures Alone all tasks, with baseline adjustment (difference score and baseline as covariate): VANILLA BASELINE

Effect	Regression Coefficient	Standard Error	*df*	*t*	*p*	C-statistic
CARDIAC MEASURES						
Mean RRI	-0.0026	0.0029	71	-0.8922	0.3753	-0.0026
SD RRI (SDNN)	0.0218	0.0097	71	2.2429	0.0280	0.0218
Min RRI/task	-0.0112	0.0039	71	-2.8363	0.0059	-0.0112
Mean HR	0.0332	0.0297	71	1.1202	0.2664	0.0332
LF HRV	5.4E-05	0.0001	71	0.3802	0.7049	0.5717
HF HRV	0.0011	0.0011	71	1.0048	0.3184	0.5592
log LF HRV	0.1213	0.2162	71	0.5611	0.5765	0.5648
log HF HRV	0.0568	0.2899	71	0.1960	0.8452	0.5645
log VLF HRV	0.2961	0.2511	71	1.1790	0.2423	0.5677
LF:HF HRV ratio	2.6E-05	0.0007	71	0.0366	0.9709	0.5433
Normalized HF HRV	-4.5761	3.3245	71	-1.3765	0.1730	0.5723
Normalized LF HRV	4.2431	3.2448	71	1.3077	0.1952	0.5726
Ventric. systole time	-0.0039	0.0075	72	-0.5228	0.6027	0.5145
Ventric. relax. Time	-0.0194	0.0157	71	-1.2356	0.2207	0.5325
Heart muscle condt'n	0.3431	0.3219	72	1.0661	0.2899	0.5587
Cardiac economics	0.0190	0.0832	72	0.2285	0.8199	0.4954
Ventric relax % RRI	-0.2326	0.1732	72	-1.3432	0.1834	0.5607
Systole % RRI	0.0568	0.1032	72	0.5510	0.5833	0.5110
BLOOD PRESSURE MEASURES						
SYSTOLIC BP	0.0246	0.0193	73	1.2773	0.2055	0.5523
DIASTOLIC BP	-0.0150	0.0232	73	-0.6478	0.5191	0.5467
RESPIRATION MEASURES						
Respiration Rate	0.0891	0.0756	60	1.1775	0.2437	0.5787
Minute vol ventil	0.0491	0.0405	60	1.2114	0.2305	0.5618
Mean ETCO2/task	-0.1101	0.1928	60	-0.5713	0.5699	0.5700
Min ETCO2/task	0.0435	0.0728	60	0.5970	0.5528	0.5427
% Sighs	0.0318	0.0396	60	0.8040	0.4245	0.5784
BODY MOVEMENT						
Movement	6.0549	2.2795	60	2.6562	0.0101	0.6591

Table 6c. Discriminating High load from Combined Medium and Low-load tasks using Physiological Measures Alone: all tasks, with baseline adjustment (difference score and baseline as covariate): COUNTING BASELINE

Effect	Regression Coefficient	Standard Error	*df*	*t*	*p*	C-statistic
CARDIAC MEASURES						
Mean RRI	-0.0076	0.0033	110	-2.3456	0.0208	-0.0076
SD RRI (SDNN)	0.0302	0.0101	110	3.0020	0.0033	0.0302
Min RRI/task	-0.0166	0.0041	110	-4.0825	0.0001	-0.0166
Mean HR	0.0873	0.0343	109	2.5456	0.0123	0.0873
LF HRV	0.0001	0.0002	110	0.5310	0.5965	0.0001
HF HRV	0.0003	0.0009	110	0.3585	0.7207	0.0003
log LF HRV	0.0905	0.2600	110	0.3481	0.7284	0.0905
log HF HRV	-0.0693	0.2302	110	-0.3010	0.7640	-0.0693
log VLF HRV	0.2020	0.2370	110	0.8526	0.3958	0.2020
LF:HF HRV ratio	0.0001	0.0006	110	0.2252	0.8223	0.0001
Normalized HF HRV	-3.9044	2.9436	110	-1.3264	0.1875	-3.9044
Normalized LF HRV	3.8302	2.8501	110	1.3439	0.1818	3.8302
Ventric. systole time	-0.0096	0.0080	111	-1.2061	0.2303	-0.0096
Ventric. relax. Time	-0.0227	0.0160	111	-1.4207	0.1582	-0.0227
Heart muscle condt’n	0.4070	0.2893	111	1.4071	0.1622	0.4070
Cardiac economics	0.1035	0.0921	111	1.1230	0.2639	0.1035
Ventric relax % RRI	-0.1574	0.1562	111	-1.0075	0.3159	-0.1574
Systole % RRI	0.1807	0.1095	111	1.6503	0.1017	0.1807
BLOOD PRESSURE MEASURES						
SYSTOLIC BP	0.0355	0.0172	113	2.0628	0.0414	0.5858
DIASTOLIC BP	-0.0124	0.0175	113	-0.7086	0.4801	0.5455
RESPIRATION MEASURES						
Respiration Rate	0.0262	0.0545	98	0.4810	0.6316	0.5316
Minute vol ventil	0.0824	0.0419	98	1.9665	0.0521	0.5684
Mean ETCO2/task	-0.0688	0.0936	110	-0.7350	0.4639	0.5661
Min ETCO2/task	-0.0428	0.0612	110	-0.6993	0.4859	0.5534
% Sighs	0.0011	0.0309	98	0.0340	0.9729	0.5218
BODY MOVEMENT						
Movement	1.1202	1.0706	98	1.0464	0.2980	0.6100

Table 6d. Discriminating High load from Medium tasks using Physiological Measures Alone: all tasks, with baseline adjustment (difference score and baseline as covariate): COUNTING BASELINE

Effect	Regression Coefficient	Standard Error	*df*	*t*	*p*	C-statistic
CARDIAC MEASURES						
Mean RRI	-0.0035	0.0035	71	-1.0022	0.3197	-0.0035
SD RRI (SDNN)	0.0326	0.0128	71	2.5461	0.0131	0.0326
Min RRI/task	-0.0133	0.0044	71	-3.0116	0.0036	-0.0133
Mean HR	0.0452	0.0356	71	1.2704	0.2081	0.0452
LF HRV	0.0001	0.0002	71	0.5604	0.5769	0.0001
HF HRV	0.0011	0.0011	71	0.9792	0.3308	0.0011
log LF HRV	0.2444	0.3019	71	0.8095	0.4209	0.2444
log HF HRV	0.0373	0.2710	71	0.1375	0.8911	0.0373
log VLF HRV	0.3384	0.2716	71	1.2459	0.2169	0.3384
LF:HF HRV ratio	0.0000	0.0007	71	0.0230	0.9817	0.0000
Normalized HF HRV	-4.3859	3.2679	71	-1.3421	0.1838	-4.3859
Normalized LF HRV	4.0396	3.1810	71	1.2699	0.2083	4.0396
Ventric. systole time	-0.0047	0.0087	72	-0.5343	0.5948	-0.0047
Ventric. relax. Time	-0.0211	0.0168	72	-1.2566	0.2130	-0.0211
Heart muscle condt'n	0.3593	0.3333	72	1.0780	0.2847	0.3593
Cardiac economics	0.0023	0.1123	72	0.0208	0.9835	0.0023
Ventric relax % RRI	-0.2553	0.1806	72	-1.4132	0.1619	-0.2553
Systole % RRI	0.0577	0.1192	72	0.4840	0.6298	0.0577
BLOOD PRESSURE MEASURES						
SYSTOLIC BP	0.0259	0.0197	73	1.3135	0.1931	0.5447
DIASTOLIC BP	-0.0102	0.0203	73	-0.5027	0.6167	0.5450
RESPIRATION MEASURES						
Respiration Rate	0.0543	0.0739	62	0.7340	0.4657	0.5366
Minute vol ventil	0.0590	0.0466	63	1.2655	0.2103	0.5563
Mean ETCO2/task	-0.0153	0.1044	71	-0.1462	0.8842	0.5479
Min ETCO2/task	0.0278	0.0671	71	0.4142	0.6800	0.5389
% Sighs	0.0206	0.0381	63	0.5424	0.5895	0.5479
BODY MOVEMENT						
Movement	5.0248	2.1766	63	2.3085	0.0243	0.6228

Table 6e. Discriminating High load from combined Medium and low-load tasks using Physiological Measures Alone: all tasks, with baseline adjustment (difference score and baseline as covariate): BREATHING BASELINE

Effect	Regression Coefficient	Standard Error	*df*	*t*	*p*	C-statistic
CARDIAC MEASURES						
Mean RRI	-0.0054	0.0026	110	-2.0873	0.0392	-0.0054
SD RRI (SDNN)	0.0263	0.0091	110	2.8847	0.0047	0.0263
Min RRI/task	-0.0139	0.0035	110	-3.9424	0.0001	-0.0139
Mean HR	0.0599	0.0266	110	2.2497	0.0265	0.0599
LF HRV	0.0001	0.0002	110	0.5878	0.5579	0.0001
HF HRV	0.0003	0.0008	110	0.3764	0.7073	0.0003
log LF HRV	0.1127	0.2481	110	0.4542	0.6506	0.1127
log HF HRV	-0.0669	0.2507	110	-0.2668	0.7901	-0.0669
log VLF HRV	0.1444	0.2159	110	0.6687	0.5051	0.1444
LF:HF HRV ratio	0.0002	0.0007	110	0.3082	0.7585	0.0002
Normalized HF HRV	-4.0696	2.9629	110	-1.3735	0.1724	-4.0696
Normalized LF HRV	4.0353	2.8736	110	1.4042	0.1631	4.0353
Ventric. systole time	-0.0081	0.0068	111	-1.1918	0.2359	-0.0081
Ventric. relax. Time	-0.0209	0.0141	111	-1.4782	0.1422	-0.0209
Heart muscle condt'n	0.3655	0.2632	111	1.3885	0.1678	0.3655
Cardiac economics	0.1076	0.0870	111	1.2361	0.2190	0.1076
Ventric relax % RRI	-0.1299	0.1373	110	-0.9455	0.3465	-0.1299
Systole % RRI	0.1407	0.0917	111	1.5355	0.1275	0.1407
BLOOD PRESSURE MEASURES						
SYSTOLIC BP	0.0338	0.0163	113	2.0750	0.0403	0.5952
DIASTOLIC BP	-0.0146	0.0190	113	-0.7700	0.4429	0.5442
RESPIRATION MEASURES						
Respiration Rate	0.0399	0.0517	110	0.7709	0.4424	0.5786
Minute vol ventil	0.0733	0.0368	110	1.9933	0.0487	0.6192
Mean ETCO2/task	-0.0518	0.0704	110	-0.7356	0.4635	0.5641
Min ETCO2/task	-0.0374	0.0549	110	-0.6804	0.4977	0.5539
% Sighs	0.0005	0.0300	110	0.0154	0.9878	0.5496
BODY MOVEMENT						
Movement	1.5626	1.0638	110	1.4689	0.1447	0.6797

Table 6f. Discriminating High load from Medium-load tasks using Physiological Measures Alone: all tasks, (difference score and baseline as covariate): BREATHING BASELINE

Effect	Regression Coefficient	Standard Error	*df*	*t*	*p*	C-statistic
CARDIAC MEASURES						
CARDIAC MEASURES						
SD RRI	0.0238	0.0028	71	2.3188	0.0233	0.0238
SD RRI/task	-0.0109	0.0038	71	-2.8522	0.0057	-0.0109
Mean HR	0.0317	0.0284	70	1.1169	0.2679	0.0317
LF HRV	0.0001	0.0002	71	0.5884	0.5581	0.0001
HF HRV	0.0001	0.0010	71	0.9639	0.3384	0.0001
HF HRV	0.2195	0.2735	71	0.8025	0.4249	0.2195
log HF HRV	0.0561	0.2803	71	0.2001	0.8420	0.0561
log HF HRV	0.2532	0.2442	71	1.0372	0.3032	0.2532
LF:HF HRV	0.0000	0.0007	71	0.0680	0.9459	0.0000
LF:HF HRV	4.4593	3.2792	71	-1.3599	0.1782	4.4593
Normalized LF HRV	4.4593	3.1838	71	1.2875	0.2021	4.4593
Ventric. systole time	-0.0042	0.0076	72	-0.5553	0.5804	-0.0042
Ventric. relax. Time	-0.0186	0.0152	72	-0.5553	0.5804	-0.0186
Heart muscle condt’n	0.3095	0.0152	72	1.0458	0.2991	0.3095
Cardiac economics	0.0197	0.1017	72	1.0458	0.8471	0.0197
Ventric relax % RRI	0.1951	0.1017	71	-1.2687	0.2087	0.1951
Systole % RRI	0.1951	0.1002	72	-1.2687	0.6181	0.1951
BLOOD PRESSURE MEASURES						
SYSTOLIC BP	0.0234	0.0180	73	1.3008	0.1974	0.5494
DIASTOLIC BP	-0.0118	0.0219	73	-0.5401	0.5908	0.5383
RESPIRATION MEASURES						
Respiration Rate	0.0608	0.0690	70	0.8812	0.3812	0.5729
Minute vol ventil	0.0520	0.0422	71	1.2338	0.2213	0.5868
Mean ETCO2/task	-0.0239	0.0781	71	-0.3060	0.7605	0.5404
Min ETCO2/task	0.0160	0.0601	71	0.2657	0.7913	0.5401
% Sighs	0.0201	0.0377	71	0.5336	0.5953	0.5796
BODY MOVEMENT						
Movement	5.5278	2.1031	71	2.6284	0.0105	0.6853

Table 7a. Discriminating High load from combined Medium and Low-load tasks using Physiological Measures Alone: tasks selected for future research, with baseline adjustment (difference score and baseline as covariate): VANILLA BASELINE

Effect	Regression Coefficient	Standard Error	*df*	*t*	*p*	C-statistic
CARDIAC MEASURES						
Mean RRI	-0.0081	0.0034	71	-2.4039	0.0188	-0.0081
SD RRI (SDNN)	0.0234	0.0103	71	2.2680	0.0264	0.0234
Min RRI/task	-0.0170	0.0046	71	-3.7176	0.0004	-0.0170
Mean HR	0.0930	0.0363	71	2.5635	0.0125	0.0930
LF HRV	0.0000	0.0001	71	0.0403	0.9680	0.0000
HF HRV	-0.0004	0.0013	71	-0.3363	0.7377	-0.0004
log LF HRV	-0.0475	0.2266	71	-0.2099	0.8344	-0.0475
log HF HRV	-0.2714	0.2982	71	-0.9100	0.3659	-0.2714
log VLF HRV	-0.0053	0.2631	71	-0.0201	0.9840	-0.0053
LF:HF HRV ratio	0.0003	0.0007	71	0.4242	0.6727	0.0003
Normalized HF HRV	-5.4485	3.8523	71	-1.4143	0.1616	-5.4485
Normalized LF HRV	-0.0475	0.2266	71	-0.2099	0.8344	-0.0475
Ventric. systole time	-0.0107	0.0082	72	-1.3086	0.1948	-0.0107
Ventric. relax. Time	-0.0217	0.0177	72	-1.2251	0.2245	-0.0217
Heart muscle condt'n	0.3653	0.4077	72	0.8961	0.3732	0.3653
Cardiac economics	0.1512	0.0953	72	1.5864	0.1170	0.1512
Ventric relax % RRI	-0.0766	0.1858	72	-0.4124	0.6813	-0.0766
Systole % RRI	0.2146	0.1166	72	1.8408	0.0698	0.2146
BLOOD PRESSURE MEASURES						
SYSTOLIC BP	0.0522	0.0205	74	2.5483	0.0129	0.6687
DIASTOLIC BP	-0.0142	0.0238	73	-0.5964	0.5528	0.5692
RESPIRATION MEASURES						
Respiration Rate	0.2359	0.0931	60	2.5350	0.0139	0.6671
Minute vol ventil	0.1000	0.0458	60	2.1837	0.0329	0.6358
Mean ETCO2/task	-0.2682	0.1953	60	-1.3733	0.1748	0.6247
Min ETCO2/task	-0.0957	0.0780	60	-1.2271	0.2246	0.5982
% Sighs	0.0318	0.0401	60	0.7934	0.4307	0.5906
BODY MOVEMENT						
Movement	8.5982	2.6077	60	3.2972	0.0016	0.7245

Table 7b. Discriminating High load from Medium-load tasks using Physiological Measures Alone: tasks selected for future research, with baseline adjustment (difference score and baseline as covariate): VANILLA BASELINE

Effect	Regression Coefficient	Standard Error	*df*	*t*	*p*	C-statistic
CARDIAC MEASURES						
Mean RRI	-0.0051	0.0036	45.0000	-1.3915	0.1709	0.6409
SD RRI (SDNN)	0.0212	0.0115	45.0000	1.8516	0.0707	0.6926
Min RRI/task	-0.0141	0.0050	45.0000	-2.8412	0.0067	0.7685
Mean HR	0.0602	0.0384	44.0000	1.5670	0.1243	0.6633
LF HRV	0.0000	0.0002	45.0000	-0.0130	0.9897	0.5740
HF HRV	0.0004	0.0014	45.0000	0.2610	0.7953	0.5893
log LF HRV	-0.0002	0.2527	45.0000	-0.0007	0.9994	0.5740
log HF HRV	-0.1781	0.3416	45.0000	-0.5212	0.6048	0.5829
log VLF HRV	0.1327	0.2983	45.0000	0.4448	0.6586	0.5548
LF:HF HRV ratio	0.0000	0.0008	45.0000	0.0587	0.9534	0.5727
Normalized HF HRV	-5.3077	4.1850	45.0000	-1.2683	0.2112	0.6135
Normalized LF HRV	4.7460	4.0434	45.0000	1.1738	0.2467	0.6116
Ventric. systole time	-0.0075	0.0091	46.0000	-0.8307	0.4104	0.5478
Ventric. relax. Time	-0.0225	0.0193	46.0000	-1.1665	0.2494	0.5389
Heart muscle condt’n	0.4134	0.4937	46.0000	0.8374	0.4067	0.5357
Cardiac economics	0.0786	0.1075	46.0000	0.7315	0.4682	0.5440
Ventric relax % RRI	-0.2158	0.2145	46.0000	-1.0060	0.3197	0.5223
Systole % RRI	0.1128	0.1258	46.0000	0.8966	0.3746	0.5402
BLOOD PRESSURE MEASURES						
SYSTOLIC BP	0.04876	0.02484	47	1.96259	0.05563	0.64668
DIASTOLIC BP	-0.011	0.02615	47	-0.4194	0.67687	0.57079
RESPIRATION MEASURES						
Respiration Rate	0.1826	0.1047	38	1.7436	0.0893	0.6505
Minute vol ventil	0.0973	0.0564	38	1.7268	0.0923	0.6339
Mean ETCO2/task	-0.0566	0.2164	37	-0.2615	0.7952	193.7716
Min ETCO2/task	0.0003	0.0839	38	0.0040	0.9968	196.1245
% Sighs	0.1061	0.0611	38	1.7372	0.0905	203.6385
BODY MOVEMENT						
Movement	7.8037	3.0323	38	2.5736	0.0141	0.7270

Table 7c. Discriminating High load from combined Medium and Low-load tasks using Physiological Measures Alone: tasks selected for future research, with baseline adjustment (difference score and baseline as covariate): COUNTING BASELINE

Effect	Regression Coefficient	Standard Error	*df*	*t*	*p*	C-statistic
CARDIAC MEASURES						
Mean RRI	-0.0109	0.0041	71	-2.6761	0.0092	-0.0109
RRI (SDNN)	0.0299	0.0120	71	2.4823	0.0154	0.0299
Min RRI/task	-0.0201	0.0053	71	-3.7761	0.0003	-0.0201
Mean HR	0.1266	0.0446	71	2.8377	0.0059	0.1266
LF HRV	0.0000	0.0002	71	0.0902	0.9284	0.0000
HF HRV	-0.0005	0.0012	71	-0.4184	0.6769	-0.0005
log LF HRV	-0.0745	0.2986	71	-0.2494	0.8038	-0.0745
log HF HRV	-0.2492	0.2708	71	-0.9202	0.3606	-0.2492
log VLF HRV	-0.0107	0.2875	71	-0.0372	0.9704	-0.0107
LF:HF HRV ratio	0.0003	0.0007	71	0.4087	0.6840	0.0003
Normalized HF HRV	-5.3248	3.8114	71	-1.3971	0.1667	-5.3248
Normalized LF HRV	4.9957	3.6554	71	1.3667	0.1760	4.9957
Ventric. systole time	-0.0145	0.0101	72	-1.4336	0.1560	-0.0145
Ventric. relax. Time	-0.0208	0.0186	72	-1.1164	0.2680	-0.0208
Heart muscle condt'n	0.3607	0.4115	72	0.8764	0.3837	0.3607
Cardiac economics	0.1904	0.1159	72	1.6425	0.1048	0.1904
Ventric relax % RRI	-0.0781	0.1838	72	-0.4249	0.6722	-0.0781
Systole % RRI	0.2535	0.1350	72	1.8772	0.0645	0.2535
BLOOD PRESSURE MEASURES						
SYSTOLIC BP	0.0579	0.0218	74	2.6535	0.0097	0.6757
DIASTOLIC BP	-0.0087	0.0205	74	-0.4257	0.6715	0.5692
RESPIRATION MEASURES						
Respiration Rate	0.1889	0.0824	61	2.2928	0.0253	0.6307
Minute vol ventil	0.1344	0.0557	62	2.4120	0.0188	0.6390
Mean ETCO2/task	-0.1033	0.1098	71	-0.9406	0.3501	0.6068
Min ETCO2/task	-0.0942	0.0712	71	-1.3225	0.1902	0.6186
% Sighs	0.0041	0.0373	62	0.1091	0.9135	0.5408
BODY MOVEMENT						
Movement	7.6852	2.5130	62	3.0582	0.0033	0.6971

Table 7d. Discriminating High load from Medium-load tasks using Physiological Measures Alone (no baseline adjustment): tasks selected for future research, with baseline adjustment (difference score and baseline as covariate): COUNTING BASELINE

Effect	Regression Coefficient	Standard Error	*df*	*t*	*p*	C-statistic
CARDIAC MEASURES						
Mean RRI	-0.0071	0.0044	45	-1.6204	0.1121	-0.0071
SD RRI (SDNN)	0.0290	0.0141	45	2.0547	0.0457	0.0290
Min RRI/task	-0.0167	0.0057	45	-2.9435	0.0051	-0.0167
Mean HR	0.0838	0.0466	45	1.7988	0.0788	0.0838
LF HRV	0.0000	0.0002	45	0.0280	0.9778	0.0000
HF HRV	0.0003	0.0013	45	0.1942	0.8469	0.0003
log LF HRV	0.0158	0.3510	45	0.0450	0.9643	0.0158
log HF HRV	-0.1735	0.3169	45	-0.5473	0.5869	-0.1735
log VLF HRV	0.1467	0.3231	45	0.4541	0.6520	0.1467
LF:HF HRV ratio	0.0000	0.0008	45	0.0474	0.9624	0.0000
Normalized HF HRV	-5.2218	4.1706	45	-1.2521	0.2170	-5.2218
Normalized LF HRV	4.6428	4.0218	45	1.1544	0.2544	4.6428
Ventric. systole time	-0.0099	0.0110	46	-0.9003	0.3727	-0.0099
Ventric. relax. Time	-0.0237	0.0204	46	-1.1587	0.2526	-0.0237
Heart muscle condt’n	0.4490	0.5274	46	0.8513	0.3990	0.4490
Cardiac economics	0.0831	0.1373	46	0.6054	0.5479	0.0831
Ventric relax % RRI	-0.2286	0.2184	46	-1.0466	0.3008	-0.2286
Systole % RRI	0.1262	0.1478	46	0.8540	0.3975	0.1262
BLOOD PRESSURE MEASURES						
SYSTOLIC BP	0.0539	0.0263	47	2.0501	0.0460	0.6467
DIASTOLIC BP	-0.0069	0.0230	47	-0.2980	0.7670	0.5772
RESPIRATION MEASURES						
Respiration Rate	0.1336	0.0918	38	1.4548	0.1539	0.6173
Minute vol ventil	0.1234	0.0671	39	1.8411	0.0732	0.6390
Mean ETCO2/task	-0.0227	0.1207	45	-0.1880	0.8517	0.5867
Min ETCO2/task	-0.0094	0.0766	45	-0.1223	0.9032	0.5625
% Sighs	0.0713	0.0529	39	1.3478	0.1855	0.6301
BODY MOVEMENT						
Movement	6.9662	2.9997	39	2.3223	0.0255	0.6913

Table 7e. Discriminating High load from combined Medium and Low-load tasks using Physiological Measures Alone, with baseline adjustment (difference score and baseline as covariate): tasks selected for future research, with baseline adjustment: BREATHING BASELINE

Effect	Regression Coefficient	Standard Error	*df*	*t*	*p*	C-statistic
CARDIAC MEASURES						
Mean RRI	-0.0076	0.0032	71	-2.3909	0.0195	-0.0076
SD RRI (SDNN)	0.0244	0.0105	71	2.3202	0.0232	0.0244
Min RRI/task	-0.0167	0.0045	71	-3.7207	0.0004	-0.0167
Mean HR	0.0859	0.0338	70	2.5416	0.0133	0.0859
LF HRV	0.0000	0.0002	71	0.1929	0.8476	0.0000
HF HRV	-0.0004	0.0011	71	-0.3405	0.7345	-0.0004
log LF HRV	-0.0268	0.2924	71	-0.0916	0.9273	-0.0268
log HF HRV	-0.2571	0.2845	71	-0.9039	0.3691	-0.2571
log VLF HRV	-0.0455	0.2484	71	-0.1833	0.8551	-0.0455
LF:HF HRV ratio	0.0004	0.0008	71	0.5124	0.6100	0.0004
Normalized HF HRV	-5.6645	3.8787	71	-1.4604	0.1486	-5.6645
Normalized LF HRV	5.4014	3.7282	71	1.4488	0.1518	5.4014
Ventric. systole time	-0.0115	0.0083	72	-1.3928	0.1680	-0.0115
Ventric. relax. Time	-0.0222	0.0173	72	-1.2784	0.2052	-0.0222
Heart muscle condt’n	0.3563	0.3902	72	0.9131	0.3643	0.3563
Cardiac economics	0.1930	0.1101	72	1.7531	0.0838	0.1930
Ventric relax % RRI	-0.0783	0.1721	71	-0.4552	0.6504	-0.0783
Systole % RRI	0.1994	0.1121	72	1.7784	0.0796	0.1994
BLOOD PRESSURE MEASURES						
SYSTOLIC BP	0.0592	0.0216	74	2.7349	0.0078	0.6891
DIASTOLIC BP	-0.0105	0.0225	74	-0.4652	0.6432	0.5462
RESPIRATION MEASURES						
Respiration Rate	0.1870	0.0769	70	2.4309	0.0176	0.6881
Minute vol ventil	0.1196	0.0495	71	2.4169	0.0182	0.7015
Mean ETCO2/task	-0.0748	0.0810	71	-0.9235	0.3589	0.5966
Min ETCO2/task	-0.0863	0.0659	71	-1.3098	0.1945	0.6180
% Sighs	0.0059	0.0362	71	0.1625	0.8713	0.5740
BODY MOVEMENT						
Movement	8.1990	2.3716	71	3.4572	0.0009	0.7851

Table 7f. Discriminating High load from Medium-load tasks using Physiological Measures Alone, with baseline adjustment (difference score and baseline as covariate): tasks selected for future research, with baseline adjustment: BREATHING BASELINE

Effect	Regression Coefficient	Standard Error	*df*	*t*	*p*	C-statistic
CARDIAC MEASURES						
Mean RRI	-0.0049	0.0035	45	-1.4109	-0.0049	0.0035
SD RRI (SDNN)	0.0229	0.0120	45	1.9043	0.0229	0.0120
Min RRI/task	-0.0136	0.0048	45	-2.8510	-0.0136	0.0048
Mean HR	0.0567	0.0362	45	1.5667	0.0567	0.0362
LF HRV	0.0000	0.0002	45	0.1028	0.0000	0.0002
HF HRV	0.0003	0.0012	45	0.2297	0.0003	0.0012
log LF HRV	0.0402	0.3264	45	0.1232	0.0402	0.3264
log HF HRV	-0.1578	0.3240	45	-0.4869	-0.1578	0.3240
log VLF HRV	0.0694	0.2742	45	0.2531	0.0694	0.2742
LF:HF HRV ratio	0.0001	0.0009	45	0.1074	0.0001	0.0009
Normalized HF HRV	-5.4332	4.2324	45	-1.2837	-5.4332	4.2324
Normalized LF HRV	4.8668	4.0843	45	1.1916	4.8668	4.0843
Ventric. systole time	-0.0080	0.0092	46	-0.8649	-0.0080	0.0092
Ventric. relax. Time	-0.0220	0.0188	46	-1.1729	-0.0220	0.0188
Heart muscle condt’n	0.3781	0.4517	46	0.8369	0.3781	0.4517
Cardiac economics	0.0949	0.1257	46	0.7553	0.0949	0.1257
Ventric relax % RRI	-0.1904	0.1953	46	-0.9752	-0.1904	0.1953
Systole % RRI	0.1023	0.1225	46	0.8353	0.1023	0.1225
BLOOD PRESSURE MEASURES						
SYSTOLIC BP	0.0448	0.0229	47	1.9502	0.0571	0.6505
DIASTOLIC BP	-0.0079	0.0249	47	-0.3173	0.7524	0.5472
RESPIRATION MEASURES						
Respiration Rate	0.1287	0.0838	45	1.5353	0.1317	0.6594
Minute vol ventil	0.1101	0.0613	45	1.7960	0.0792	0.6773
Mean ETCO2/task	-0.0342	0.0903	45	-0.3790	0.7065	0.5791
Min ETCO2/task	-0.0174	0.0711	45	-0.2444	0.8080	0.5791
% Sighs	0.0710	0.0518	45	1.3710	0.1772	0.6830
BODY MOVEMENT						
Movement	7.1814	2.7716	45	2.5911	0.0129	0.7679

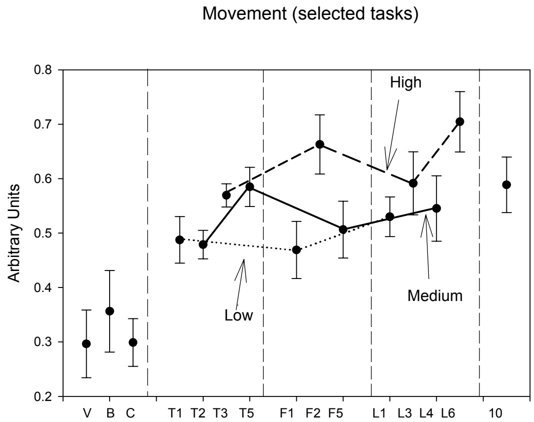
6.1. Body movement from motion detector (figitometer)

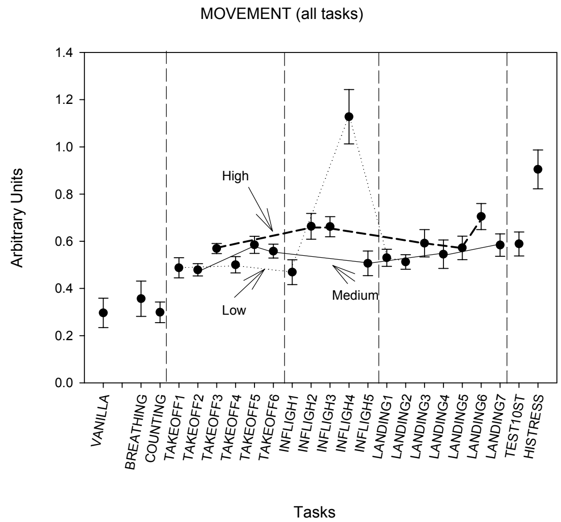
In general, more motion was detected in high-load than in medium or low-load tasks (Fig 1). This may be influenced to some degree by greater muscular demands of the tasks (i.e., greater muscular effort involved in managing the controls). Although muscular activity could possibly affect autonomic activity independently of work load, we have chosen not to eliminate its effects statistically because, if one thinks of the body as an integrated mechanism, in which physical as well as mental effort work together to produce "task load" effects, then motion can be considered an aspect of task load rather than an artifact.

There was one anomaly. One low-load task, F4, weather front penetration, produced, by far, the highest values for this measure. Given that this task produced relatively small cardiorespiratory effects, we concluded that the increase in motion was caused by movement of the simulator itself, produced by simulation of weather activity, rather than movement by the subject, and should be eliminated in future research determining standard task for evaluating physiological arousal produced by tasks of known vs. unknown load.

Applying a random effects logistic regression model we found significant contrasts for High vs. medium load tasks, both for all tasks and for tasks selected for future research, with and without control for baseline (Tables 5-8). The C-statistic showed body movement alone to be a poor detector of flight task load when calculated for all tasks, and a fair predictor when calculated among tasks chosen for future research. Including baseline adjustments in the statistical model tended to improve detection.

Fig. 1. Movement





Note: In all figures where abbreviations are used, tasks are denoted as follows:
V = Vanilla baseline B = 6/min breathing tasks
C = Counting task T1—L7 = Flight tasks
10 = 10-sec flight task
HS = high stress (high-demand) task (not included in this graph because it was off scale)

Because body movement may be considered as a rough index of physical effort involved in various tasks, below, in discussion of physical vs. mental effort on the TLX, we include analyses in which cardiac and respiratory measures are controlled for body movement, in order to determine whether results are entirely due to effects of muscular demands of various tasks, or whether added autonomic effects occur, perhaps related to mental effort, where this can be distinguished from physical effort. We note, however, that the two are not always distinguishable. It has long been known that mental effort alone usually is accompanied by increases in muscle tension (Freeman, 1931; Hadley, 1941). These findings have held up in recent research as well (Bloemsaat et al, 2005; Schleifer et al, 2008).

6.2. Heart Rate (HR) and Heart Rate Variability (HRV)

A summary of significant cardiac findings is presented in Table 8.

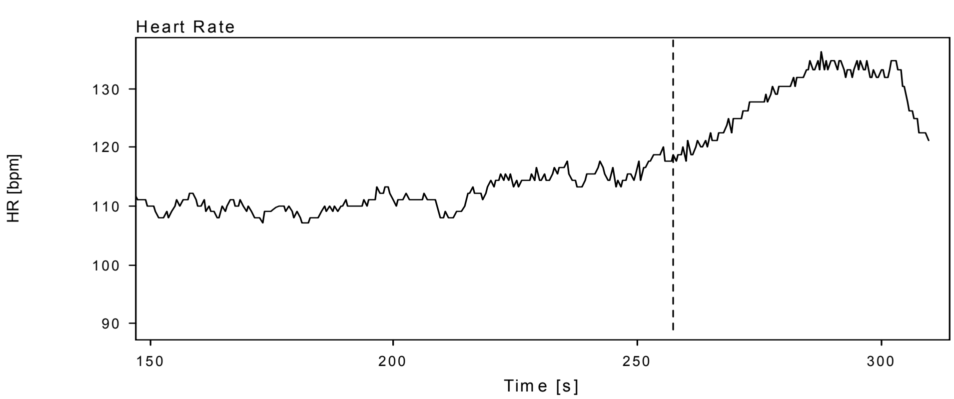
Table 8. Significant cardiac discrimination between High load and either Combined Medium and Low load or Medium load alone, for all tasks and tasks selected for future research (*p* values)

Variable and tasks	no baseline	vanilla	counting	breathing
MEAN RRI				
Medium and Low				
All		0.04	0.03	0.04
Selected	.06 for HR	0.04	0.03	0.05
Medium				
All		0.03		
Selected				
SDNN				
Medium and Low				
All	0.05	0.009	0.004	0.005
Selected	0.1	0.009	0.004	0.005
Medium				
All	0.09	0.006	0.02	0.03
Selected		0.03		0.03
MIN RRI				
Medium and Low				
All	0.0002	0.0002	0.0001	0.0002
Selected	0.0007	0.0002	0.0001	0.0002
Medium				
All	0.06	0.006	0.004	0.006
Selected	0.05	0.006	0.004	0.006

6.2.1. Heart Rate

Heart rate was very responsive to task demand. Fig 2 shows typical heart rate changes during a high-load task.

Fig. 2. Subject 5 Landing 6
Heart Rate with Landing Gear Stuck Up (high demand)



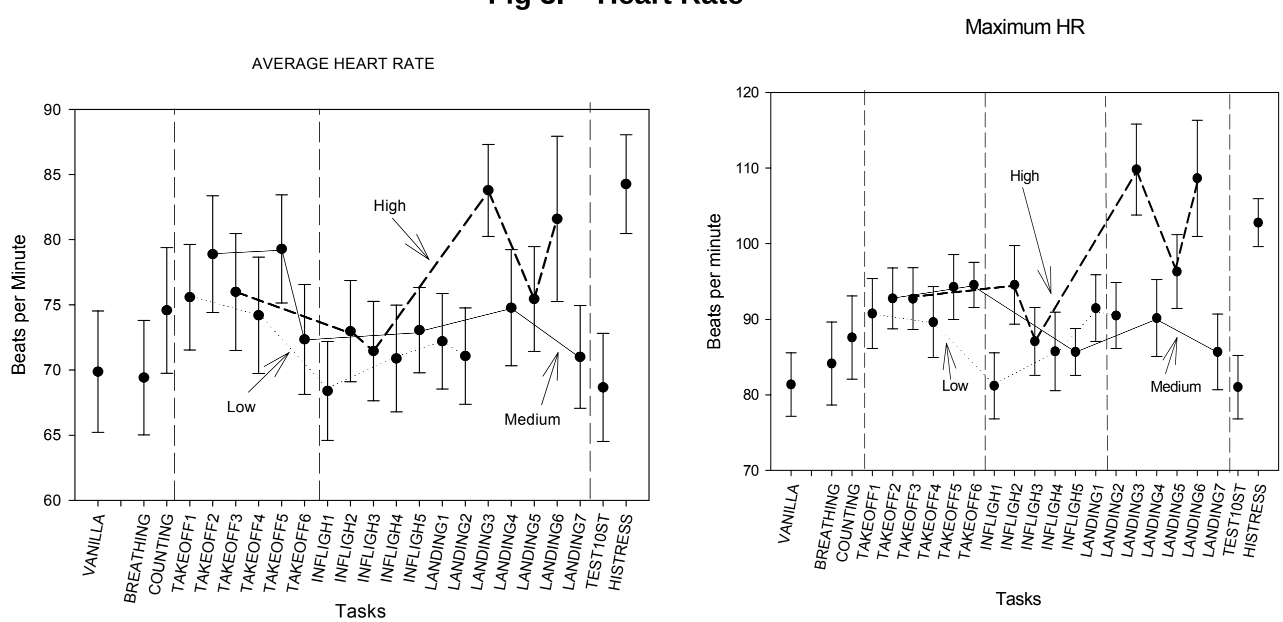
A sharp increase in heart rate occurred during landing without a landing gear. Heart rate was otherwise not particularly high, although there was a small anticipatory response when the pilot first discovered that a problem may have occurred. Note that mean HR was over130 beats/minute for about 20 seconds.

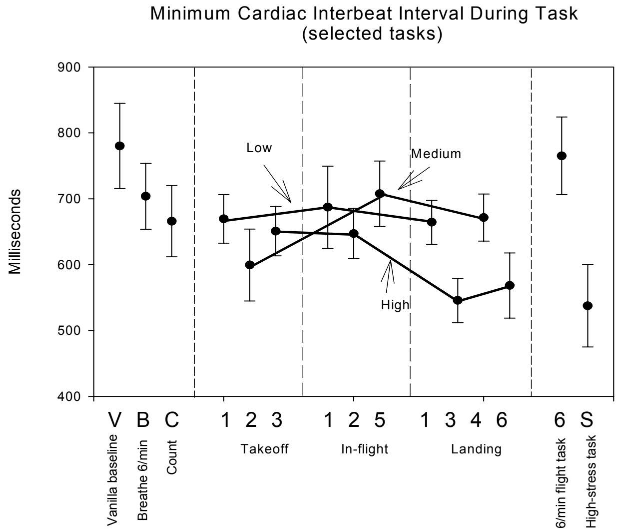
Fig 3 shows average HR and the maximum level of heart rate during each of the tasks, averaged across the seven subjects. HR was generally higher during high-load tasks than low-load ones, with medium-load tasks showing intermediate values. Medium-demand tasks showed a more inconsistent pattern, sometimes similar to high-demand tasks (T2, engine fire, L4, wind shear), and sometimes to low-demand tasks (T1, normal takeoff, and T4, low-visibility takeoff) . Note that HR was higher during takeoff than flight tasks. This probably reflects the fact that these tasks occurred first during testing. HR also was higher during high-demand landing tasks than in high-demand takeoff or flight tasks. Other studies also have found higher HR during landing than during various takeoff and flight tasks (Lee & Liu, 2003; Jorna, 1993; Kramer, Sirevaag, & Braune, 1987; Veltman, & Gaillard, 1998). The cognitive and physical demands involved in landing an aircraft appear greater than those involved in various takeoff or flight events.

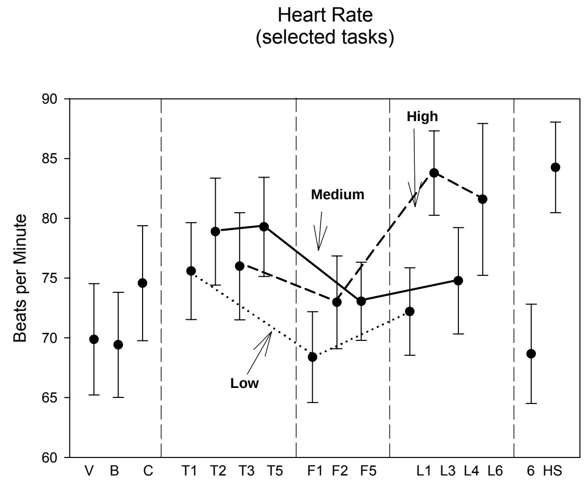
Speed of the heart during “events” (e.g., report of wind shear, touchdown, etc.) quantified as the maximum heart rate for each task, showed somewhat clearer differentiation between high and low-demand tasks than mean HR for the entire period.

Note that for both measures of HR, the level was higher during flight tasks than during the vanilla and counting baseline tasks. HR is usually elevated in “active coping” situations (Obrist, 1976 1981), and high-load landing activity apparently activates such a response, approximately equaling the response during the maximal load task. Slightly higher HR during takeoff than flight tasks may reflect more active coping, or the fact that these tasks were given first. In any psychophysiological testing environment, physiological arousal tends to be higher during the first few minutes of testing (Myrtek, Dieterle, Wilfried, 1990). Jorna, 1993, Veltman & Gaillard, 1998). Fig 3 shows cardiac interbeat interval (R-R interval from the EKG) in milliseconds, to illustrate an alternative method for quantifying speed of the heart. It shows information similar to heart rate, but with the direction inverted (higher interbeat intervals being a function of lower heart rate).

Fig 3. Heart Rate





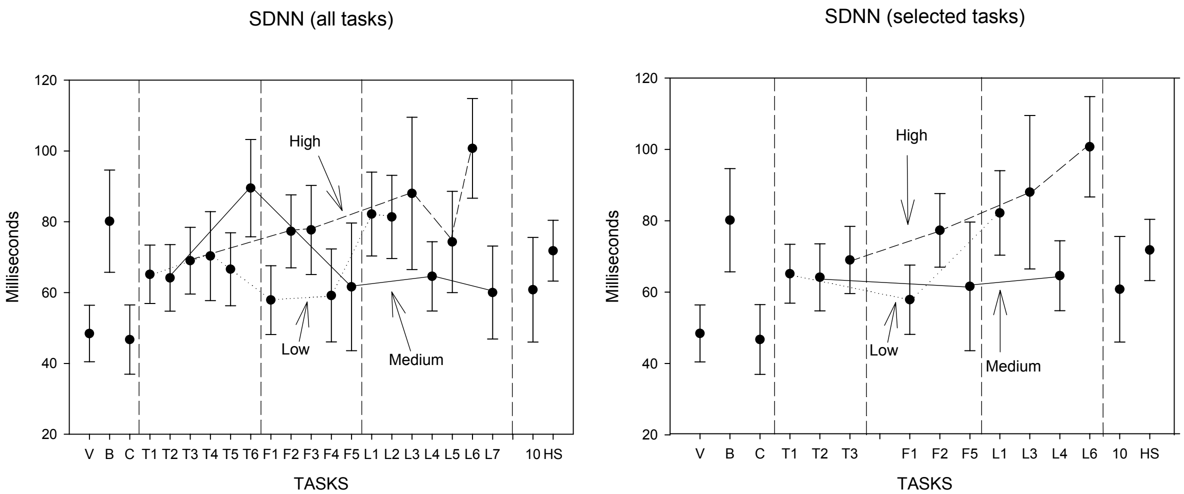


A regression analysis on data from all flight tasks (Tables 5-8) found significant effects among *a priori* task load levels for minimum RRI (i.e., maximum heart rate) during tasks for discriminating High load tasks from Medium load tasks and from combined Medium and Low-load tasks, with and without baseline corrections, with all tasks or just tasks selected for future research. The C-statistic shows that minimum heart rate alone tends to produce “fair” to “good” discrimination between High load and other tasks. Analyses on tasks selected for future research shows the same pattern of significant detection, with “good” detection for high vs. combined medium and low load tasks, and “fair” detection for high vs. medium load tasks.

6.2.2. Standard deviation of normal R-R intervals (SDNN)

In calculating all HRV measures, including SDNN, we first eliminated artifact manually and then eliminated effects of premature or skipped eats using interpolation, yielding an RRI record of only “normal” beats, reflecting normal central nervous system control of heart rhythm. SDNN tended to be higher for high-load tasks than for low and medium-load tasks, presumably because of the large changes in heart speed during “events” occurring during the tasks.

Fig 4. SDNN



A regression analysis on data from all flight tasks (Tables 5-8) found significant effects among *a priori* task load levels for SDNN during tasks for discriminating both High from combined Medium and Low-load tasks and High from Medium tasks. However, among tasks selected for future research, discrimination of High from Medium load tasks was significant only with Vanilla and Breathing baseline corrections. The C-statistic shows that SDNN alone produces “poor” to “fair” discrimination both between high load and other tasks, with discrimination slightly better with baseline corrections.

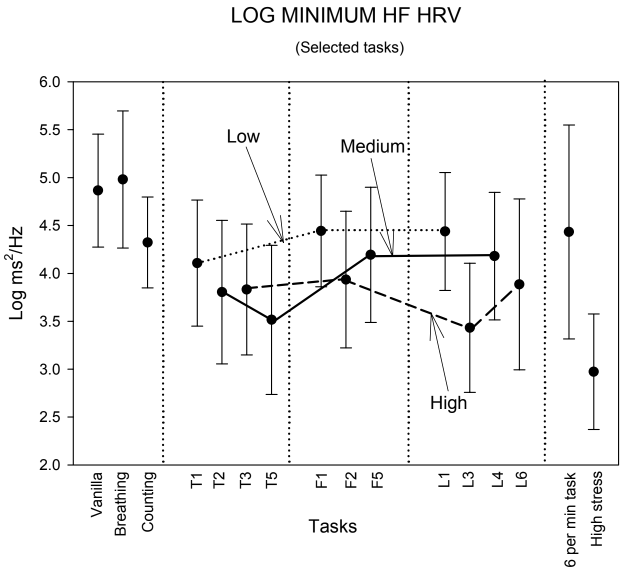
6.2.3. High frequency HRV (HF HRV)

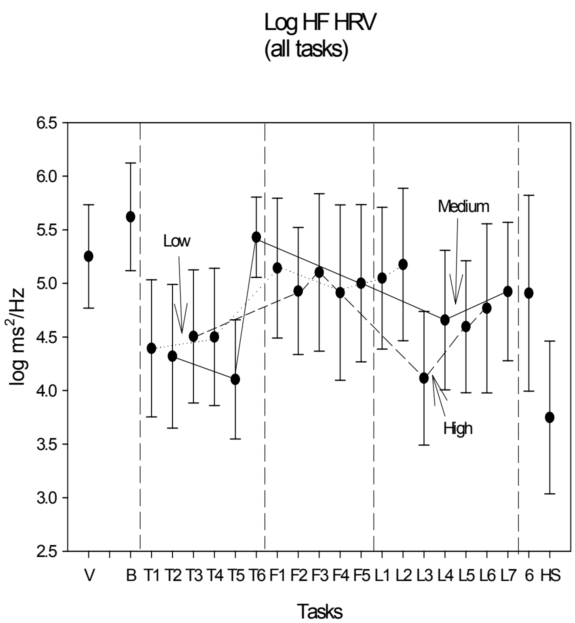
HF HRV was calculated from results of a fast Fourier transformation, of consecutive normal RRI’s. It was defined as the spectral power of HRV within the frequency range of 0.15-0.4 Hz. All HRV data were analyzed statistically after a log transformation, in order to adjust for inherent non-normality in these data. There were no statistically significant differences between tasks of differing *a priori* flight task load.

Nevertheless, when we examined HF HRV among individual subjects during the highest-load “events” in each task, HF HRV appeared to be depressed in high-demand tasks relative to other tasks in some of the subjects, with no clear pattern in others. To find specific responses to high-load events during the tasks we divided the tasks into four periods of 1.25 minutes, and analyzed the period with the lowest HF HRV.

Note the nonoverlapping distribution for values during all of the baseline task and the very high stress task (Fig 5). (The high standard errors result from inter-subject variability on all measures; standard errors will decline with a larger population of subjects. Therefore a larger trial will result in clearer differentiation among load levels.) Landing tasks, which generally put higher demand on pilots, showed better HF HRV task load differentiation than takeoff or in-flight tasks.

Fig 5. High Frequency Heart Rate Variability

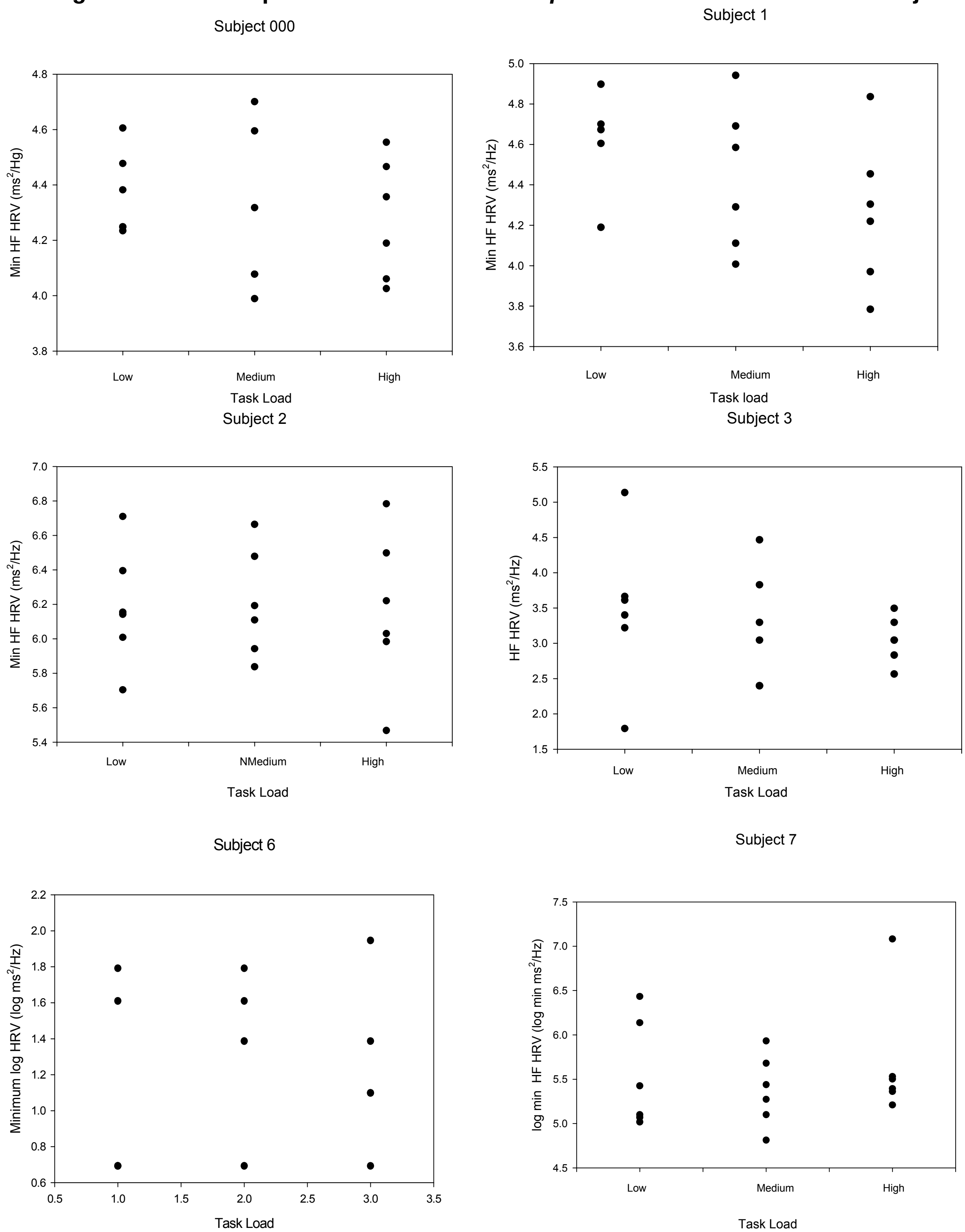




Baseline = vanilla task; L = low demand;
M = medium demand;
H = high demand;

While not all subjects showed a clear pattern of lower HRV at higher-*a-priori* task demand tasks, half of them did show such a pattern, but with some overlap between load levels (Subjects 0, 1, and 3 in Fig 5), while others showed no clear pattern.

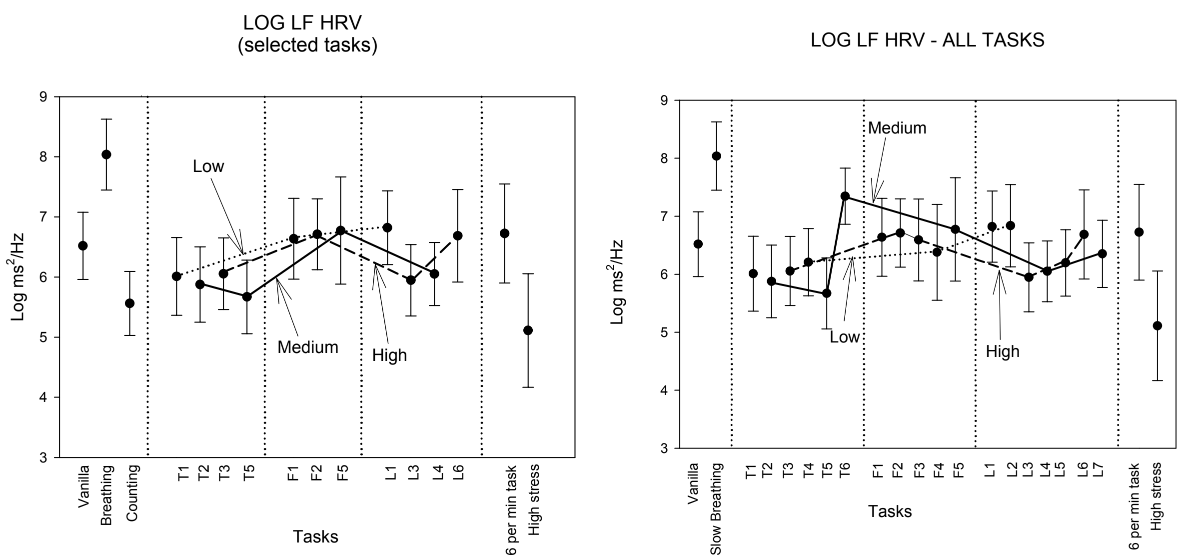
Fig. 6. Relationship between HF HRV and *a priori* task demand for each subject



6.2.4. Low-frequency HRV (LF HRV)

LF HRV was defined as the spectral power of consecutive normal RRI's within the range of 0.15-0.4 Hz. LF HRV was high during the 6/min breathing and flight tasks, because heart rate changes were stimulated by physiology or flight tasks, respectively for the two tasks, within this frequency range. There were no significant differences in LF HRV among levels of flight task load. Fig 7 shows a lower level for the very high-load task, compared with the vanilla baseline. No statistics could be done on this comparison, because only three subjects were tested in the high-load task. If this comparison were verified in future research, the result would be consistent with prior literature characterizing depressed LF HRV as reflecting task involvement. Nevertheless, for other flight tasks, there was little differentiation among levels of flight task load on this measure. It is possible that the insensitivity of this measure was partially due to the fact that autonomic effects of specific events during the tasks tended to be rather brief, but LF HRV requires at least three minutes' of stable activity for reliable assessment, so we could not calculate a value for it during specific task "events."

Fig. 7. Low frequency HRV

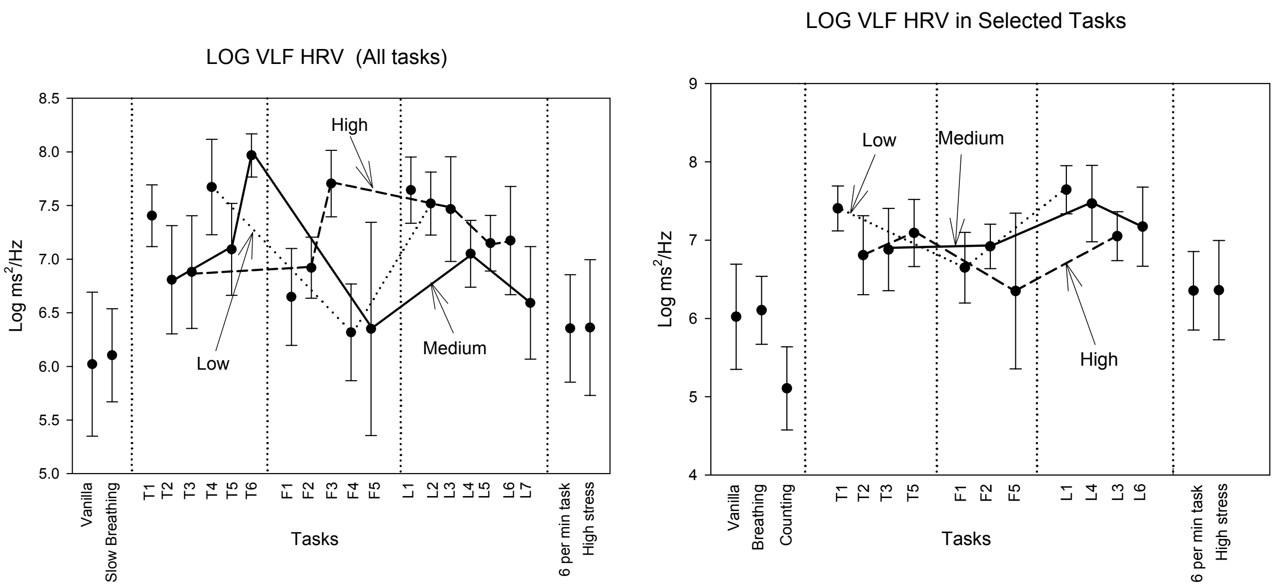


6.2.5. Very low frequency heart rate variability (VLF HRV)

We analyzed VLF HRV despite the short recording period, which would call this measure into question as a reflection of heart rate *oscillations,* and, hence, sympathetic activity. However, this measure did reflect slow changes in HR during the task, perhaps event-related.

VLF HRV was not significantly related to *a priori* ratings of task load. The inconsistent relationship between VLF HRV and task demand (Fig 8) suggests that VLF HRV may not be a good measure of task demand. Indeed, most psychophysiological studies leave out this measure, partially because stationarity can rarely be guaranteed for a sufficiently long time to assess true HR oscillations in the VLF range.

Fig. 8. Very Low Frequency HRV



6.2.6. The LF:HF HRV ratio

Often used to assess autonomic balance, the LF:HF ratio did not predict level of *a priori* task load in this study.

6.2.7. Measures of cardiac function

We also analyzed several measures of heart function to determine whether workload involved in any of the flight tasks interfered with mechanical function of the heart. The measures are summarized in Table 9. Although we found no differences among *a priori* task workload conditions, we did find a significant relationship with pilot performance (see below).

Table 9. Measures of heart function (from shape of the EKG wave)

ECG QT	Ventricular systole time (Time period of the ventricular systole)
ECG TaTe	Ventricular relaxation time
Heart muscle condt'n	Heart muscle Condition [arb] = (RTa - RSe)/TaTe
ECO	Cardiac economics (Eco [%]) = (QT/Mean RRI)*100%
Relax	Ventricular relax time (% RRI) = (TaTe/ Mean RRI)*100%
Syst	Systole time (% RRI) = (RTa/ Mean RRI) *100%
RTa	Time between R and T wave apex, ventricular systole time
Ta or Sa	Apex of T or S wave
QT, RT, etc.	Time between Q and T wave, R and T wave, etc.

See Fig. 9 for a diagram of the QRST complex of the EKG wave. See discussion of these definitions in (Bundzen et al, 1991; Dibner and Koltuk,1990)

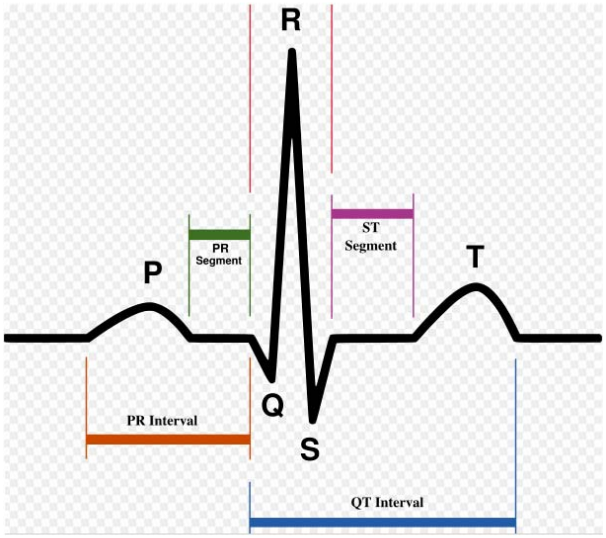


Fig. 9. QRST Complex from the EKG wave (from *Wikipedia*, 'Electrocardiogram')

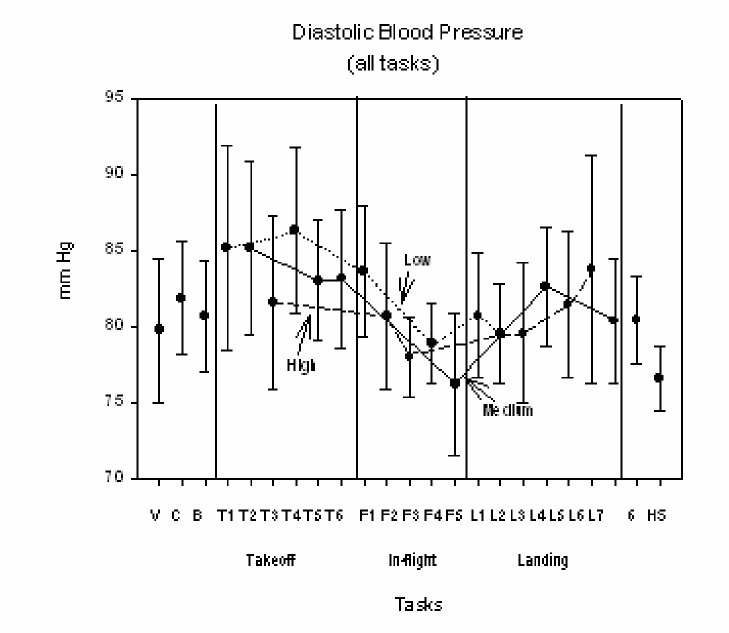
6.3. Blood pressure

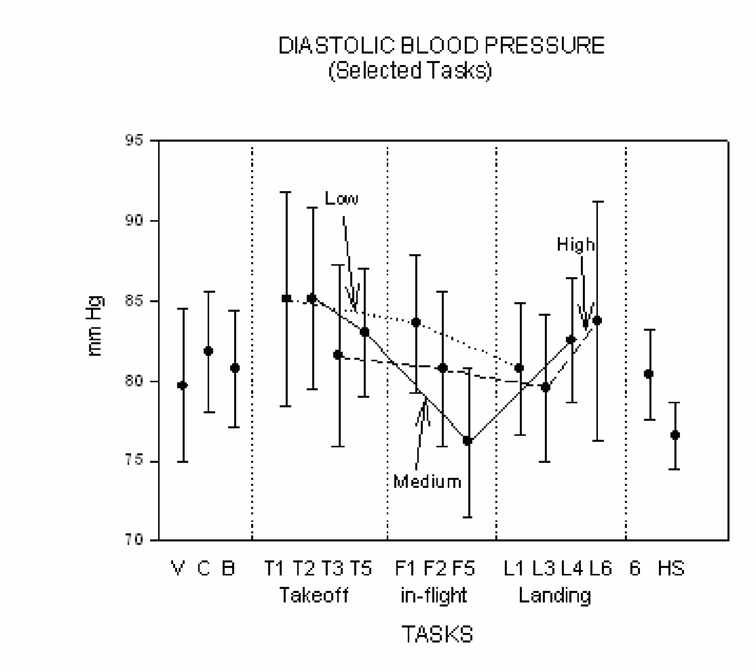
Blood pressure was an inexact measure in this study, because it was taken after each task rather than during it. Thus many changes in blood pressure probably were missed. Nevertheless, major changes occurred across tasks in this measure. In general, Systolic measures tended to be more closely related to *a priori* load than diastolic. With considerable overlap, high-load tasks tended to be followed by higher Systolic BP levels than low- and medium-load tasks.

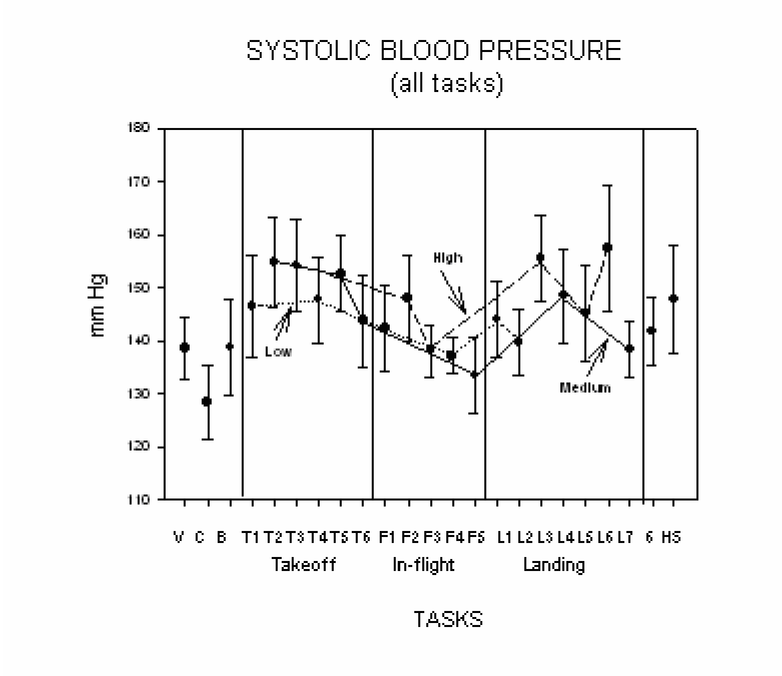
As in all physiological measures, there was a pronounced "order" effect. Systolic BP (Fig 10) was highest during the Takeoff tasks, probably because these were presented first. Diastolic blood pressure (Fig 10) appeared marginally higher in some low-load tasks.

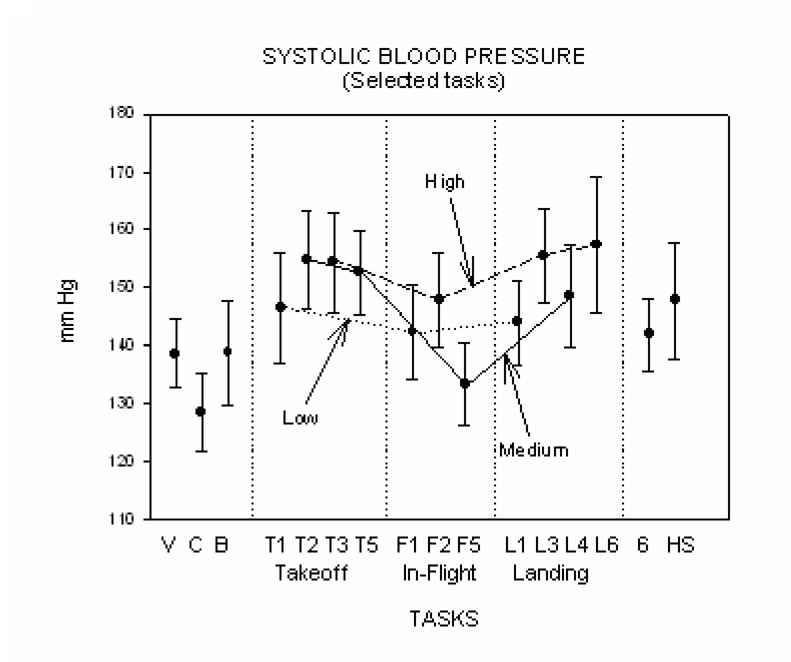
Regression analyses found that systolic blood pressure significantly discriminated High from combined Medium and Low-load tasks when analyzed in all tasks, with baseline adjustments (Tables 5-7), but only at a borderline level ($p < .08$) without baseline adjustment. The C-statistic indicated that detection was "poor" to "fair".

Fig 10. Systolic/ Diastolic Blood Pressure









6.3.1. Hypertensive reactions.

This study demonstrated that clinically significant hypertensive reactions can be produced by high-stress flight simulator tasks.

BP is one of the "end products" of physiological regulation. It may be expected to rise under high demand tasks, to force more blood into needy muscular and brain cells, when more activity occurs or is expected. Generally, however, increases are small and fleeting, except under severe muscular exertion or severe stress. Such increases are not pathological, if recovery occurs rather quickly; indeed, aerobic exercise causing increases in BP is thought to be therapeutic for various cardiovascular diseases. However, for sedentary work, increases in either diastolic or Systolic BP above 160/90 can pose some risk in susceptible individuals, particularly if prolonged and frequent. We found such increases to be common among high-demand tasks among older subjects, but not among younger subjects (Table 10). Some subjects were obviously hypertensive, however, and would not be representative of line pilots. Nevertheless, these data suggest that some high-stress tasks may conceivably produce prolonged hypertensive reactions even among healthy subjects, particularly those over age 45, where various neurocardiovascular control reflexes tend to show smaller amplitude, perhaps increasing cardiovascular vulnerability to stress. The three youngest subjects in our sample, ages 35 (Subject 0), 39 (Subject 7), and 44 (Subject 1), did not show any hypertensive BP readings (Table 10). Subject 005, age 61, had Systolic BP recordings greater than 160 for all flight tasks, and above normal blood pressure for baseline tasks as well. He appears to have uncontrolled hypertension. We list tasks producing readings of least 6 mm Hg greater than 185 mm Hg.

Table 10. Incidences of high blood pressure

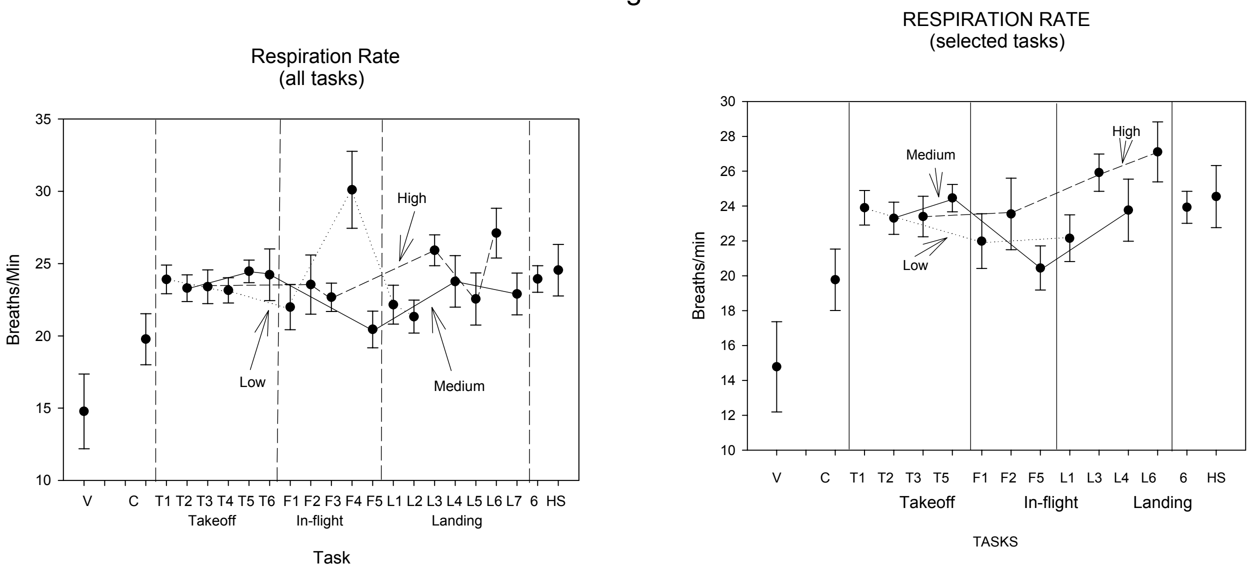
Subject #	Task	Load Level	BP	Age
002	L3	High	167/81	49
003	High Stress	High	163/72	52
003	L3	High	161/69	
003	T2	Medium	165/89	
005				
	L3	High	192/103	61
	L5	High	191/103	
	L6	High	219/119	
	T2	Medium	191/107	
	T3	High	198/106	
006	F2	High	169/71	61
006	L2	Low	163/72	
006	L3	High	160/67	
006	L4	Medium	166/72	
006	L6	High	169/76	
006	T1	Low	164/73	
006	T2	Medium	171/74	
006	T3	High	170/66	
006	T5	Medium	173/68	
006	T6	Medium	162/73	

[1] LifeShirt®, VivoMetrics, Inc., Ventura, CA, 2005

6.4. RESPIRATION

6.4.1. Respiration rate

Fig. 11



(Note: the slow-breathing task was not included in this graph because, with all subjects breathing at ~six breaths/min, the value was off scale, and including it would have reduced the ability to display differentiation among other tasks.)

Respiration rate increased in all flight tasks relative to baseline values, but the increase tended to be greater in tasks with high demand (see Fig. 11). The high-demand landing tasks evoked a greater increase in respiration rate than the takeoff or flight tasks, and better differentiation among levels of task demand.

The exception was F4 (weather front system penetration), a low-load task. In this task, rhythmical movement of the cabin appeared to produce artifact, as witnessed by greatly increased motion detection and fluctuations in the respiratory tracings that got tallied as "breaths", while minute volume of ventilation did not increase. Apparently motion of the cabin produced irregularities in the respiration record that were recorded as breaths, as well as producing increases in motion detection, but did not affect the other respiratory measures. We believe that this task should not be used as a standard for evaluating tasks of unknown load, and that respiration in other tasks involving rhythmical jerky motions of a flight simulator similarly cannot be evaluated.

Logistic regression analysis (Tables 5-7) found that respiration rate significantly distinguished High from combined Medium and Low-load tasks among tasks selected for future research, with "fair" ability to detect differences between load levels. Between-task differences were significant only in analyses of tasks selected for future research, for distinguishing High from combined Medium and Low-load tasks. Respiration rate distinguished High from Medium load tasks only controlling for the vanilla baseline, among tasks selected for future research.

Significant and near-significant respiratory data findings are summarized in Table 11.

Table 11. Significant and near significant findings among respiratory variables for discriminating among *a priori* task loads

Variable and tasks	no baseline	Vanilla	counting	Breathing
Minute volume ventilation				
Medium and Low				
All	0.08	0.08	0.06	0.05
Selected	0.03	0.04	0.02	0.02
Medium				
All				
Selected		0.10	0.08	0.08
RESPIRATION RATE				
Medium and Low				
All				
Selected	0.03	0.02	0.03	0.02
Medium				
All				
Selected		0.09		

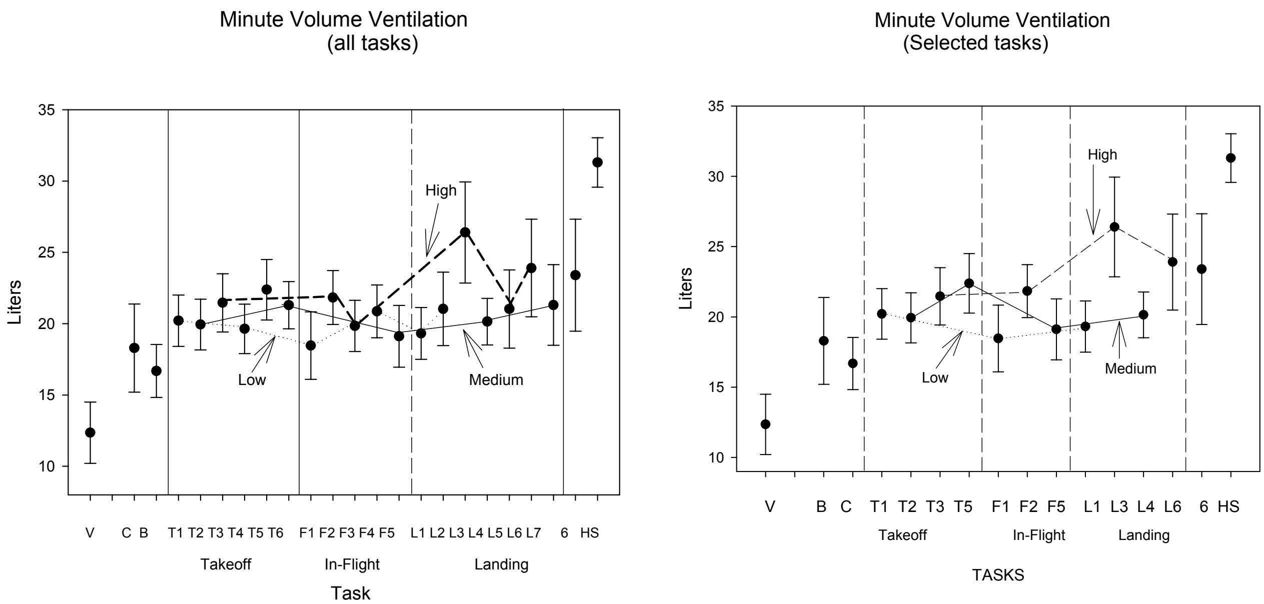
6.4.2. Minute volume ventilation (MVV)

MVV is a measure of the amount of total ventilation. Increased muscular exertion usually increases metabolic need for ventilation, causing an increase in this measure. In the absence of changes in metabolic need, however, as often occurs during situations of stress, increases in MVV can result in decreased blood levels of carbon dioxide, and this may contribute to hypocapnia.

MVV was higher in high-demand than low-demand tasks, reflecting greater ventilation. MVV was particularly high in two of the three high-demand landing tasks, L3 and L6 (elevator quadrant jam and landing gear stuck up). It was not as high in L5 (low-altitude wake turbulence), probably because the problem was not detected by the pilot throughout the task, so ventilation was not elevated for the complete task duration, although our measure of MVV was for the average of the entire five-minute period. As in respiration rate, the high-demand landing tasks evoked a greater ventilatory response than the high-demand takeoff or flight tasks, and landing tasks showed greater task load differentiation than takeoff and in-flight tasks. As expected, the combination very-high-demand task produced the highest MVV, while the plain vanilla baseline task produced the lowest level.

Logistic regression analyses found that MVV discriminated between high and combined medium and low-load tasks significantly with and without baseline adjustments, among tasks selected for future research, and, at a borderline level of significance for analyses among all tasks. Borderline discrimination of High from Medium load tasks was obtained with all baseline controls among tasks selected for future research. (Tables 5-7 and 11). Level of discrimination, based on the C-statistic, was between poor and fair.

Fig 12. Minute volume ventilation

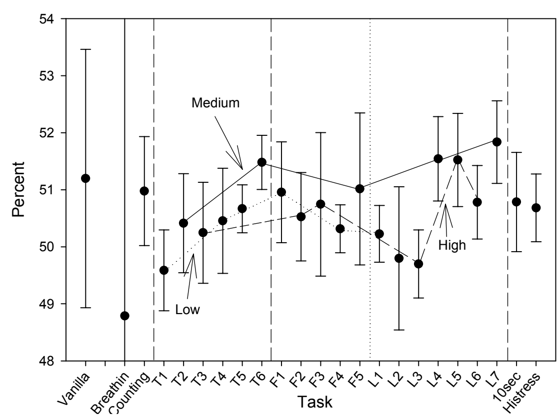


6.4.3. Time to reach peak inspiratory flow / inspiratory time

The ratio of time to reach peak inspiratory flow / inspiratory time did not significantly discriminate high-demand tasks from medium and from the combination of low and medium-demand tasks (Fig. 13). Although this measure can be interpreted as a measure of ventilatory drive, perhaps related causally to total ventilation, we are cautious about interpreting these data because of the unusual pattern of results, with nonsignificantly higher levels in moderate-load tasks than in high and low-load tasks.

Fig 13.

Time to reach peak inspiratory flow / inspiratory time
(all tasks)



6.4.4. Percent inspiratory time and sighs

Another measure of respiratory drive is the percent of total breath time in inspiration. There were no significant differences among load levels in the inspiratory/expiratory time ratio or inspiratory time as a percentage of total breath time. Neither was there an association between load level and sighs as a percentage of total breaths, or tidal volume, both of which also are related to air intake.

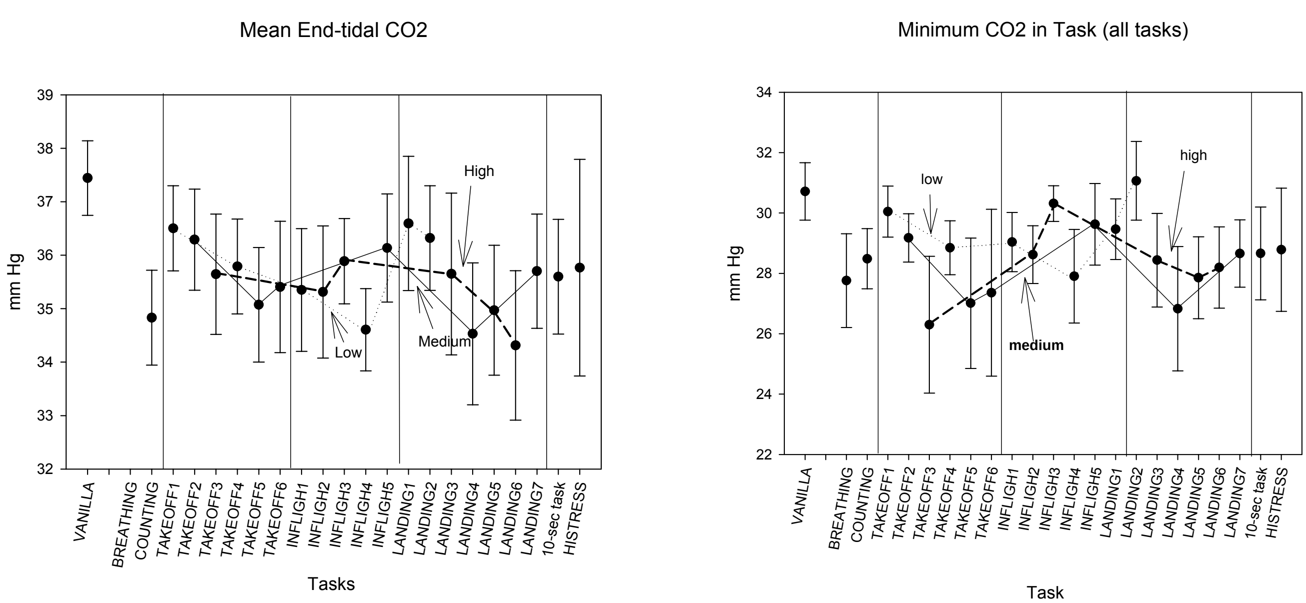
6.4.5. End-tidal carbon dioxide ($ETCO_2$)

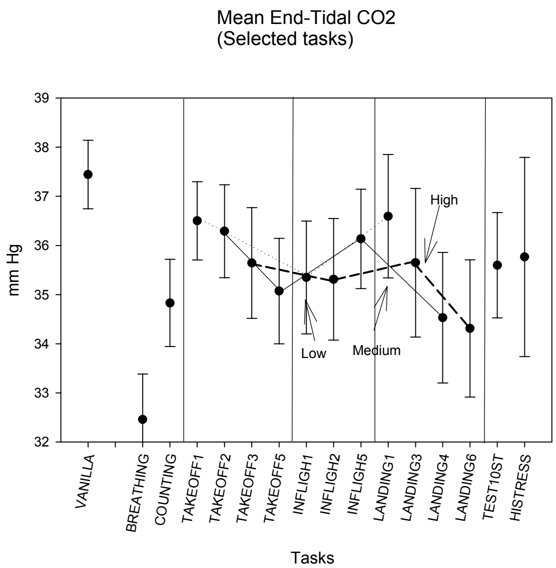
The plain vanilla task yielded values close to the expected average relaxed $ETCO_2$ (Fig 14), which usually is close to 40 mm Hg. $ETCO_2$ subsequently dropped during nearly all flight tasks. The 6/min breathing task also decreased $ETCO_2$ and induced hypocapnia in some subjects, as has been reported elsewhere for similar breathing tasks (Lehrer et al., 1997).

$ETCO_2$ did not differ significantly among flight tasks carrying varying work loads, either for the average of the entire task or the minimum values in each task (Fig 14). However all tasks showed lower values than the plain vanilla baseline task, suggesting that all tasks required some metabolic adjustments that caused a temporary decline in blood concentrations of CO_2.

Readings were particularly low for F4 (weather front penetration), where movement of the cabin may have caused the sensor to slip or the subject to take incomplete breaths. We believe that these readings were artifacts, and should not be interpreted.

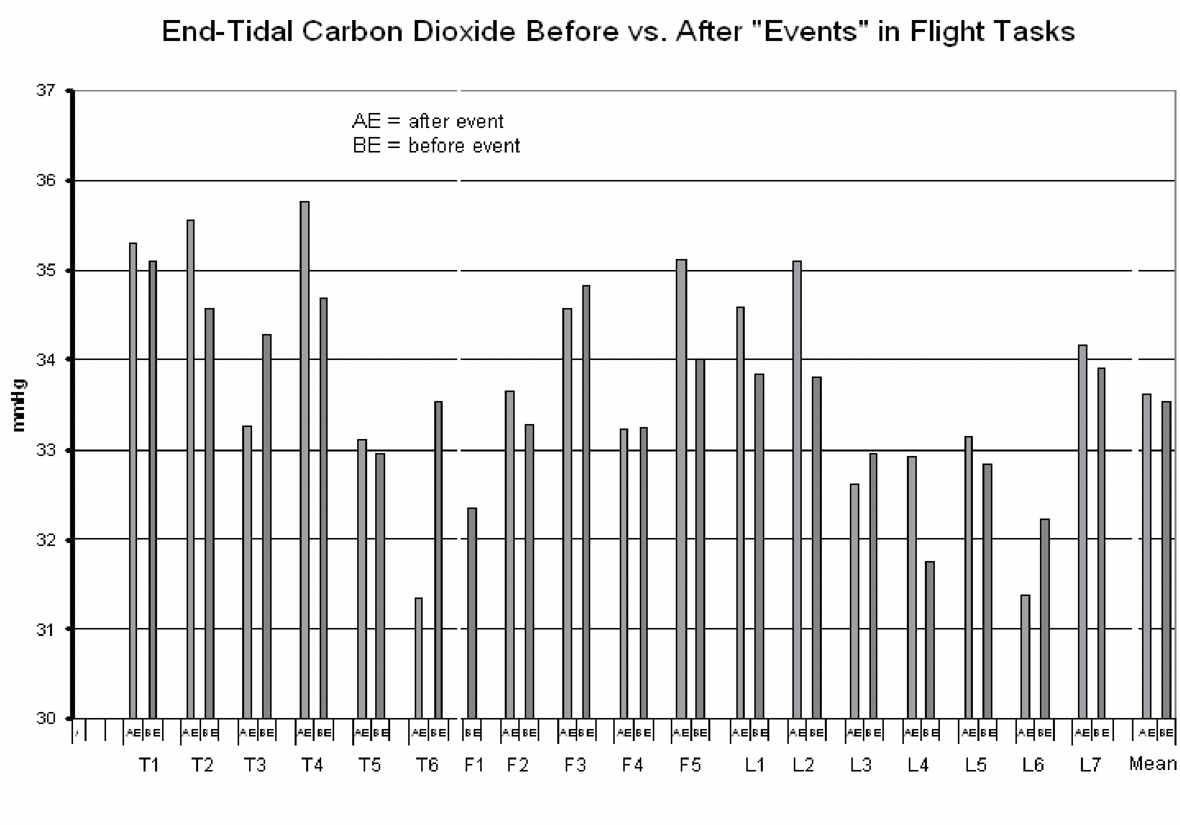
Fig. 14. End-tidal carbon dioxide





There is some evidence for small drops in $ETCO_2$ in anticipation of almost all "events" in flight tasks, regardless of flight task load. (Fig. 15) In most subjects, $ETCO_2$ rose after the event had ended.

Fig. 15**.**



6.4.5.1. Hypocapnia

Because tasks that often produce $ETCO_2$ readings < 32 mm Hg will decrease profusion of blood to the brain, and thus risk a decrease in mental and physical capacity, we also examined the frequency and duration of episodes reaching this criterion.

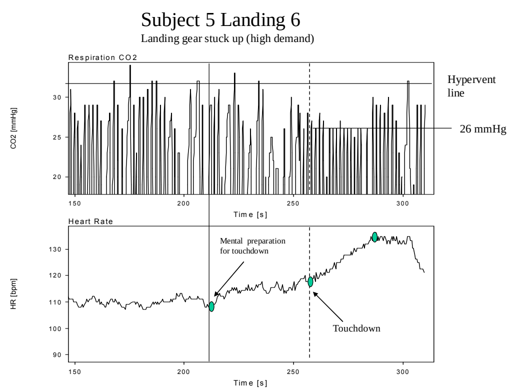
In scoring hypocapnia episodes, we required a duration of at least 15 consecutive seconds at < 32 mm Hg of $ETCO_2$, separated by, at most, one breath with a normal value. Hypocapnia occurred in a number of tasks. Changes in brain blood flow (which would immediately cause changes in thinking, etc.) occur almost without delay during hypocapnia. We have chosen 15 seconds as a cutoff in order to insure that measurement was reliable (i.e., occurring over several breaths). It also is a sufficiently long time for poor decision making to have an important impact on success in critical maneuvers.

That said, however, the degree of hypocapnia required for a practically significant decrease in pilot performance has not been definitively established.

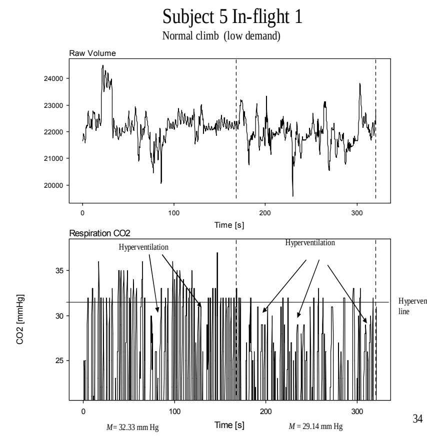
Two participants, Participants 5 and 6, showed period of hypocapnia for 40-55 seconds, certainly a sufficient time for cognitive impairment to occur. Two such events occurred in high-demand tasks (Manual reversion or elevator quadrant jam landing [L3] and Low altitude severe wake turbulence encounter (200') during approach [L5]), and one in a moderate-demand task (Landing into a moderate to severe wind-shear [L4]). One subject even showed a prolonged hypocapnia episode during a normal landing procedure (L1) and during instrument landing with low visibility (L2), perhaps because he anticipated higher-load tasks. Hypocapnia periods of 10 seconds or more occurred for individual subjects in tasks T2 (engine fire upon takeoff), T3 (takeoff into wind shear), L6 (landing with one main gear stuck up), and L7 (terrain avoidance).

Subject 5 also hyperventilated in L6 (stuck landing gear [*a priori* high load]), where he also displayed a large increase in heart rate and depth of breathing (Fig.16). A period of hypocapnia also occurred even after touchdown, but breathing was less irregular, and $ETCO_2$ did not fall as low. However Subject 5 also hyperventilated during a low-stress task (F1, normal climb), perhaps more a characteristic of the individual than of the task. It is possible that this occurred because F1 was the first in-flight task presented --- an “order” effect. Also, people with some metabolic disorders sometimes hyperventilate for physiological reasons, as a mechanism by which the body compensates for some abnormally functioning organs. This subject also showed high blood pressure, which, in some people, may be indicative of a kidney disorder, which could produce hypocapnia.

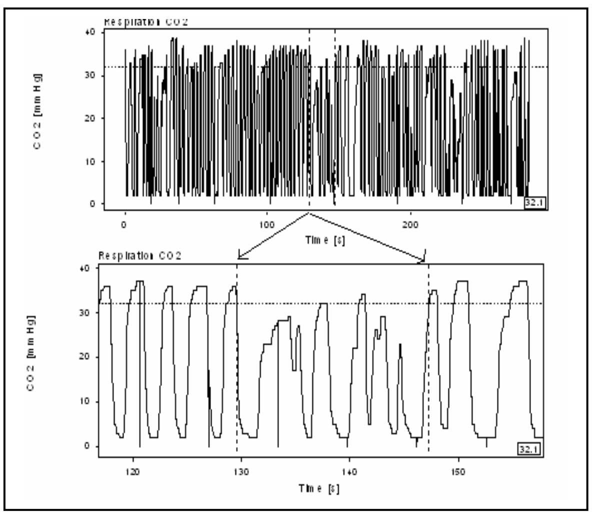
Fig 16. Examples of hypocapnia in flight tasks



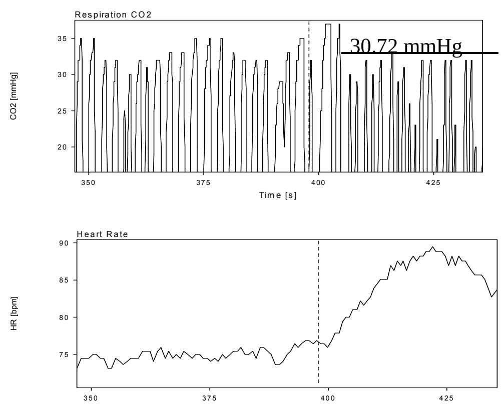
Top shows hyperventilation for ~ 30 sec. Bottom shows accompanying large increase in heart rate (ca. 20 beats/min). But ETCO2 is more irregular before touchdown than afterward. 29



Subject 3 In-flight 2, Severe Wake Turbulence



Subject 6 Takeoff 6
(brake failure during taxi)



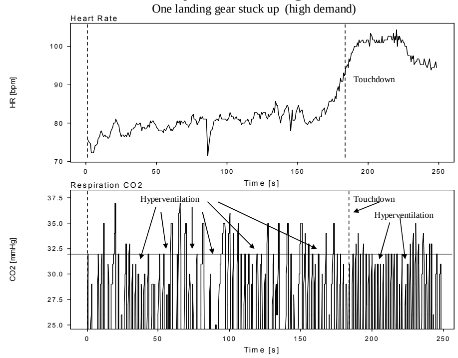
The third section of Fig 16 shows calculation of a hypocapnia episode. Note one breath above 32 mm Hg during the interval, which we ignored in calculating duration of a hypocapnia episode. Note that, in all cases, hypocapnia was accompanied by pronounced elevations in heart rate.

Subject 6 showed borderline hypocapnia in task F3 (rapid depressurization, high demand), along with an increase in respiration rate (Fig 17). This subject also hyperventilated during L6 (landing gear stuck up, high demand, Fig 17), but also showed some hypocapnia in response to a moderately demanding task, L4 (landing in wind shear conditions). ETCO2 was lowest and most irregular in *anticipation of* the wind shear event, but rose and became more regular afterward.

Subject 5 showed a pattern of hypocapnia even in low-demand tasks, but this was markedly accentuated during the landing procedure where an elevator quadrant jam was presented as the task.

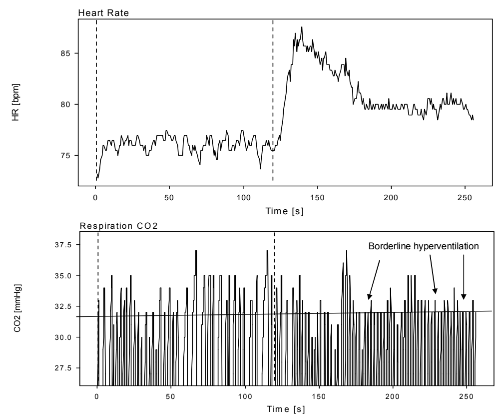
Fig. 17. Additional examples of hypocapnia

Subject 6 Landing 6
One landing gear stuck up (high demand)



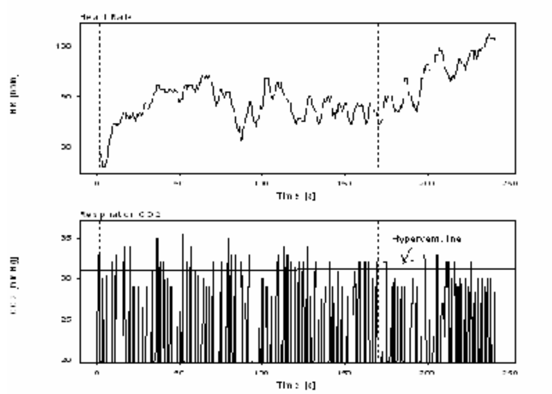
Average CO2 before and after touchdown was almost the same, but after touchdown CO2 was more stable. 32

Subject 6 Flight 3 – Rapid depressurization
High demand



35

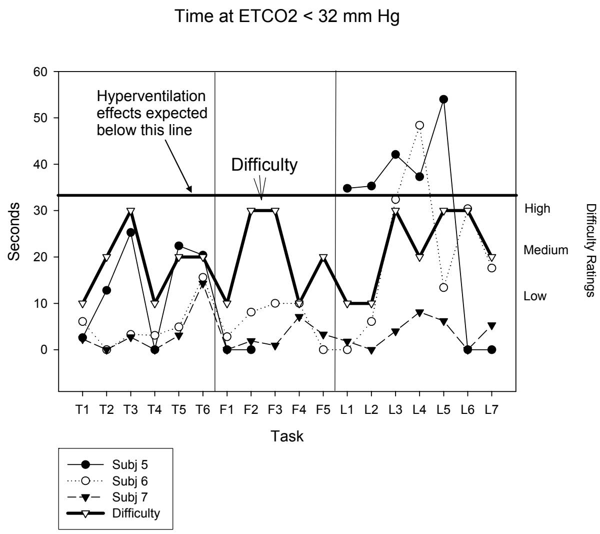
SUBJECT 5 Landing 3
(Elevator quadrant jam)

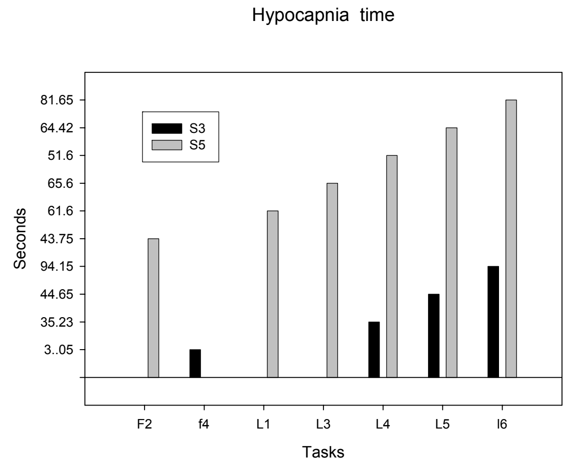


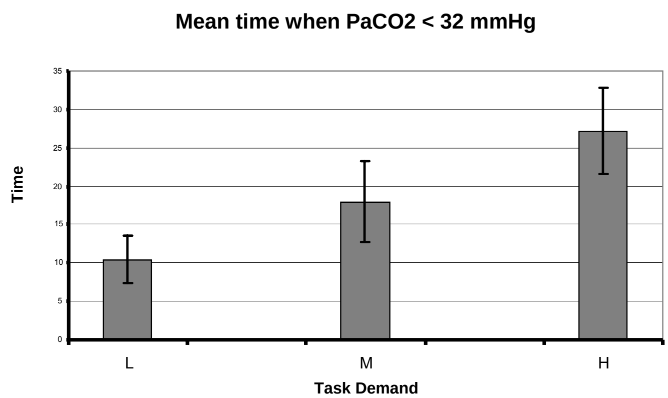
The fact that hypocapnia episodes were noted in three of six subjects with $ETCO_2$ data shows that such episodes do occur during flight tasks, and can even be elicited in the flight simulator, where the pressures are obviously much less than in real flight.

Fig. 18 shows the *duration* of hypocapnia episodes for three subjects (subjects 5, 6, and 7). Note that they correspond to task load: higher load is related to longer duration of hypocapnia episodes. Because of equipment failure, Subject 5 was not tested in Events F3, F4, and F5.

Fig. 18. Hypocapnia time







Discrepancies between self-report of work load and hypocapnia

There were some specific discrepancies that are of practical significance: cases where the subject reported “moderate” or “low” work load on the TLX, but where they hyperventilated to a clinically significant extent. We believe that this illustrates the importance of taking this physiological measure during assessment of flight task loads. The TLX is scored on a 1-100 scale, where 50 can be considered moderate (See Table 12):

Table 12. TLX Scores Where Subjects Evidenced Hypocapnia

Subject and TLX Scale	**TLX score**	**Task**
Mental Demand How mentally demanding was the task?		
Subject 005	45	L6 (landing gear stuck)
Subject 006	25	F3 (sudden depressurization)
Subject 007	75	F3 (sudden depressurization)
Physical Demand How physically demanding was the task?		

Subject 005	70	L6 (landing gear stuck)
Subject 006	25	F3 (sudden depressurization)
Subject 007	35	F3 (sudden depressurization)
Temporal Demand How hurried or rushed was the pace of the task?		
Subject 005	55	L6 (landing gear stuck)
Subject 006	20	F3 (sudden depressurization)
Subject 007	70	F3 (sudden depressurization)
Performance How successful were you in accomplishing what you were asked to do?		
Subject 005	30	L6 (landing gear stuck)
Subject 006	25	F3 (sudden depressurization)
Subject 007	50	F3 (sudden depressurization)
Effort How hard did you have to work to accomplish your level of performance?		
Subject 005	80	L6 (landing gear stuck)
Subject 006	15	F3 (sudden depressurization)
Subject 007	50	F3 (sudden depressurization)
Frustration. How insecure, discouraged, irritated, stressed, and annoyed were you?		
Subject 005	20	L6 (landing gear stuck)
Subject 006	10	F3 (sudden depressurization)
Subject 007	80	F3 (sudden depressurization)
TOTAL		
Subject 005	50	L6 (landing gear stuck)
Subject 006	20	F3 (sudden depressurization)
Subject 007	60	F3 (sudden depressurization)

Note: All tasks were rated *a priori* by FAA staff as posing high demand.
Subject 5 for L6: total TLX rated “moderate”
Subject 6 for L3: total TLX rated “low”
Subject 7 for L3: total TLX rated slightly above “moderate”

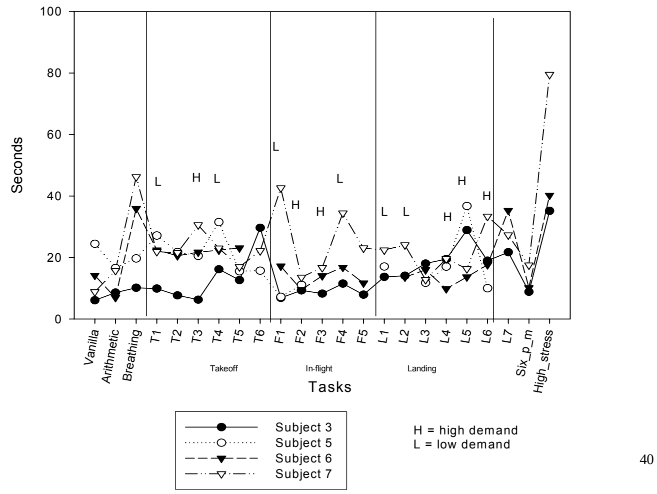
6.5. Eyeblink frequency

We recorded the time between each blink from surface EMG electrodes placed lateral to each eye, and analyzed the point in the session at which the maximum time between blinks occurred. We only have these data for subjects 3, 5, 6, and 7. Because of the small number of subjects, we did not perform statistical analyses on this measure.

Usually blinking slows during periods of stress, or where visual scanning of the environment is demanded by the task. We found that this was not universally the case among flight tasks (Fig 19). Examples of changes in blink frequency during task “events” are shown in Fig 19. In general, it appears that there were fewer blinks during landing than takeoff or in-flight tasks, with one subject (Subject 3) also showing a decrease in blinking during high-demand tasks, compared to low-demand tasks. The one exception was the first task, a normal takeoff, where blink rate tended to be low.

Fig. 19.

Time Between Blinks



Anticipation of a high-load appears to have activated eyeblinks. In Fig. 20 note that average seconds between eyeblinks was higher before events in low-load tasks was greater than for high-load tasks in selected tasks showing pronounced psychophysiological effects. The exception was T1 (normal takeoff). This task generally showed elevated psychophysiological arousal because it was the first task given.

Fig 21 shows the pattern of blinks during approach in Landing task 5 (approach with severe wake turbulence, a high demand task) for one subject, illustrating the pattern of frequent blinks prior to the event, but a decrease in blinking rate while the pilot coped with the problem.

Fig. 20

Pre-event Blinks

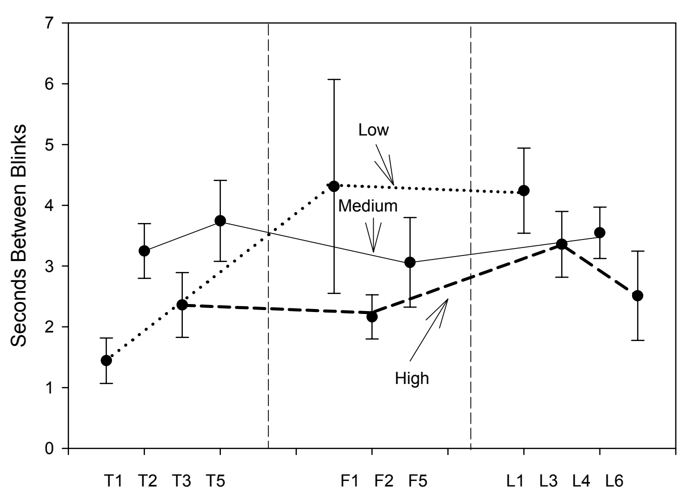
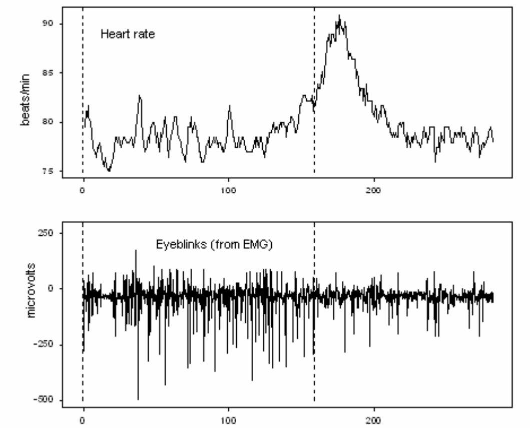


Fig. 21
SUBJECT 6 Landing 5 (Wake turbulence during approach High demand task)



7. NASA's TLX SCALE: RELATIONSHIP TO *A PRIORI* TASK DIFFICULTY AND TO PHYSIOLOGICAL MEASURES

7.1. Relationship between TLX values and *a priori* ratings of load

The association between *a priori* level of task load and total TLX score was high, regression coefficient = 0.086, s.e. = 0.021, *df* = 73, *t* = 4.137, *p* < .001 with task load as a categorical variable, and, when task load is treated as a continuous variable, regression coefficient = 12.8898, s.e. = 1.2634, dif = 134, *t* = 10.20, p <.0001. The *p* values are the same when we analyzed only tasks chosen for future research.

We also computed an ROC curve, to measure the how well a particular test detects a particular criterion (in this case, *a priori* rating of a task as producing a high workload). The ROC curve yielded C = .881 for differentiating High load from a combination of Medium and Low loads, which classifies the TLX as a "good" measure (see footnote), and C = .802 ("good") for differentiating High load from Medium load. This value may be inflated because the TLX and *a priori* load values both are ratings of subjective assessments of load by pilots, and also because some of the same people who determined the *a priori* levels also were subjects in this study. Despite this, "good" still indicates that improvement is nevertheless desirable for assessing flight task load, where accuracy of the measure is important.

Tasks rated *a priori* as "high load" were almost always rated highest on the total TLX score (Fig 21), and tasks with *a priori* ratings of "low load" were usually rated the lowest. Although tasks with *a priori* "medium load" were usually rated between the two extremes, there was some inconsistency in this category. Medium load tasks T5 (engine separation) and L4 (wind shear) were rated close to some high load tasks, while T6 (loss of brakes) was rated close to some low load tasks. Alternatively, one could say that one low load task (T4, low visibility takeoff) was rated as close to medium load, as was one high load task (L5 wake turbulence landing).

7.1.1. Physical vs. mental load

Among *a priori* low load tasks, mental load was rated slightly higher than physical load (Fig 21). Among "high load" tasks, ratings tended to be higher for physical than mental load, with the exception of F2 (wake turbulence), where mental load was higher (Fig 21). For "medium load" tasks, mental and physical loads were approximately equal for landing tasks, but mental load was higher for in-flight tasks, as was also the case for T6 (loss of brakes). In general, takeoff and landing tasks were rated as having equal or greater physical than mental load, compared with the in-flight tasks, where mental load was higher.

The mental arithmetic task was very high in mental activity, but low in physical activity. In Fig 21 the difference between physical and mental load was so large that we omitted this task from the figure so that other task differences can be seen.

The C statistic was slightly higher for physical load (C = .890 [“good”] for differentiating High from combined Medium and Low, and C = .816 [“good”] for differentiating High from Medium load tasks), than for mental load (C = .803 [“good”] for differentiating High from combined Medium and Low, but C = .611 [“poor”] for differentiating High from Medium load tasks).

7.5. Mental:physical demand discrimination:

Heart and respiratory activity directly responds to metabolic need, which is influenced by muscle activity. Muscle activity burns sugar, and utilizes oxygen, which needs to be transported to the muscles by respiratory activity (changes in ventilation) or cardiovascular activity (changes in heart rate or heart stroke volume, blood pressure, etc.). We found a small positive correlation between the ratio of physical to mental demand on the TLX and the LF:HF HRV ratio, suggesting that dominance of physical (vs. mental) load increases sympathetic dominance over parasympathetic activity. To a lesser extent, VLF HRV tended to correlate *positively* with mental demand, but not with physical demand. In this case, VLF HRV probably reflects changes in heart rate occurring during “events” in tasks. HRV measures thus may be useful for separately evaluating physical and mental demand of various flight tasks.

Another method for examining physical vs. mental load is to examine an indirect measure of physical load, our motion detector. Table 13 shows the effects of controlling for motion detector effects, in assessing the relationship of other physiological variables to *a priori* ratings of task load. We found minimal effects of adjusting for motion. Thus, we can conclude that cardiovascular and respiratory relationships with task load do not simply reflect degree of physical activity demanded by tasks of varying loads, despite the fact that higher-demand tasks had greater physical demand. Rather, physiological measures appear to be related to other aspects of “effort”, including mental effort, the *emotional* effects of high physical and mental demand, etc.

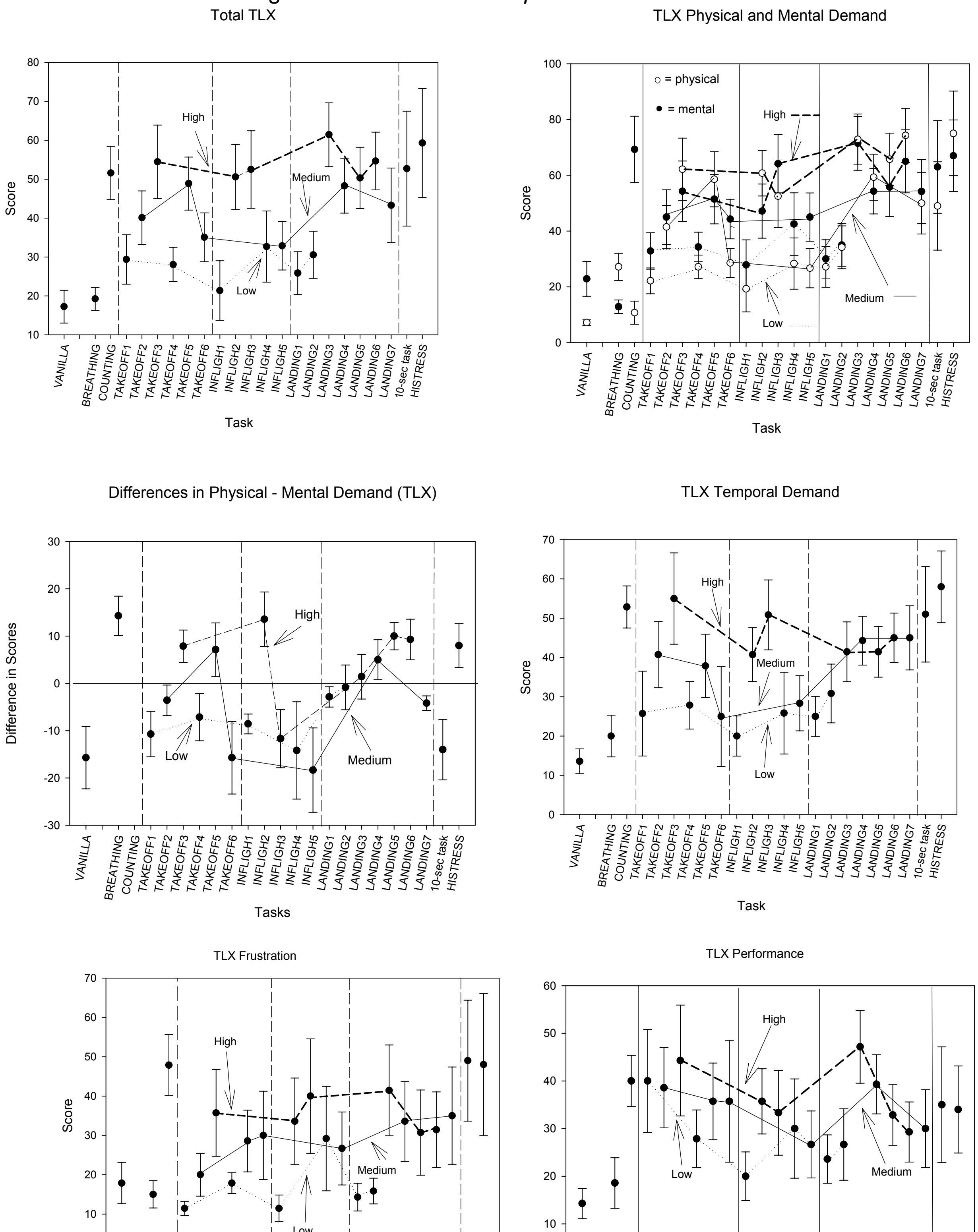
Table 13. Effect on *p* and C-statistic values of adding motion detector data to statistical model for detection of High vs. Low-load *a priori* differences: all tasks, controlled for deviation from vanilla task and total TLX values.

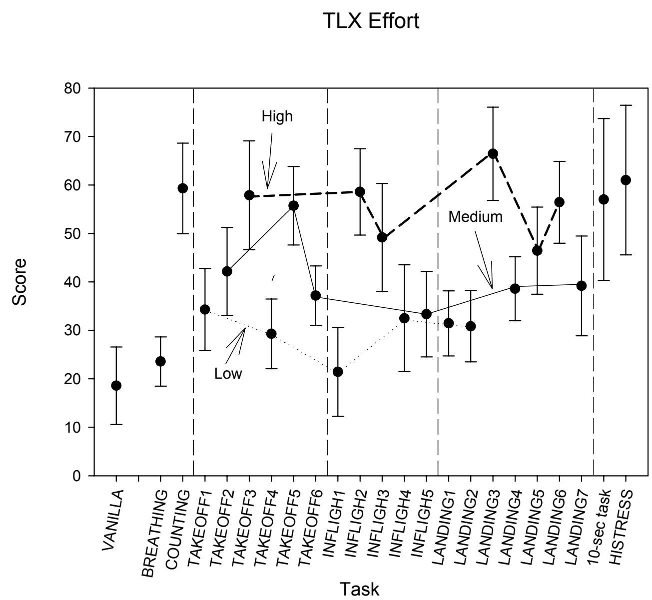
Physiological system	Effect	Not controlled for motion		Controlled for motion	
		p	C-statistic	*p*	C-statistic
Heart	Mean RRI	0.3515	0.8801	0.6707	0.8847
	SD RRI (SDNN)	0.0070	0.9012	0.0069	0.9048
	Min RRI/task	0.0110	0.8901	0.0182	0.8970
	Mean HR	0.2822	0.8792	0.5330	0.8844
	LF HRV	0.1769	0.8898	0.2011	0.8921
	HF HRV	0.4550	0.8827	0.3461	0.8913
	log LF HRV	0.0803	0.8936	0.1446	0.8970
	log HF HRV	0.3408	0.8870	0.2914	0.8936
	log VLF HRV	0.1173	0.8847	0.1302	0.8936
	LF:HF HRV ratio	0.5579	0.8807	0.8497	0.8878
	Normalized HF HRV	0.1358	0.8850	0.4147	0.8884
	Normalized LF HRV	0.1392	0.8853	0.4243	0.8887
	Ventric. systole time	0.3550	0.8563	0.3552	0.8655
	Ventric. relax. Time	0.2506	0.8604	0.5445	0.8674
	Heart muscle condt'n	0.3140	0.8606	0.1666	0.8683
	Cardiac economics	0.9055	0.8586	0.5315	0.8695
	Ventric relax % RRI	0.2926	0.8629	0.7148	0.8683
	Systole % RRI	0.5757	0.8557	0.3464	0.8640
Blood pressure	SYSTOLIC BP	0.2005	0.8791	0.1797	0.8916
	DIASTOLIC BP	0.1524	0.8903	0.3205	0.8919
Respiration	Respiration Rate	0.7120	0.7742	0.3552	0.7811
	MVV	0.2589	0.7757	0.5445	0.7789
	Mean ETCO2/task	0.1227	0.7760	0.5315	0.7765
	Min ETCO2/task	0.9905	0.7724	0.7148	0.7785
	% Sighs	0.1080	0.7803	0.3464	0.7837

7.1.2. Other TLX scales.

Other dimensions of workload assessed by the TLX include effort, frustration, and self-estimate of performance quality. Results for various TLX subscales were similar to those for the full scale, with a relatively high relationship between *a priori* rating of task difficulty and TLX responses (Fig 21).

Fig 21. TLX Values and *a priori* Task Demand





7.2. Statistical relationship among 1) TLX scores 2) *a priori* load ratings 3) performance ratings by check pilot and 4) physiological measures.

7.2.1. Relationship between TLX and 1) evaluator score and 2) *a priori* workload

To evaluate the association between TLX and both *a priori* estimates of task demand and performance (evaluator scores by the check pilot), we computed within-subject correlations across the 18 flight tasks.

As illustrated in Table 14, correlations between *a priori* load ratings (with low demand = 1, medium demand = 2, and high demand = 3) and most TLX scores tended to be moderate to high in most subjects, but low in Subject 5 and, for several scales, Subject 1. Generally correlations were lower for the Frustration scale and higher for the Physical demand scale. Correlations also were higher for physical demand than for mental demand. Correlations between TLX scores and Evaluator scores tended to be negative and low in most subjects, with the exception of the Temporal and Performance measures, where four of six were moderate. Higher self-rated task load was, to a small degree, related to poorer performance.

Table 14. Pearson within-subject Correlations: TLX Self-Ratings with Evaluator Performance Score and *a Priori* Task load

Subject	NASA TLX measure	Evaluator Score	*a priori* workload
0	Mental Demand	-0.0027	**0.6919**
1	Mental Demand	-0.2147	**0.7842**
2	Mental Demand	-0.2588	**0.5791**
3	Mental Demand	**-0.5215**	**0.4908**
5	Mental Demand		0.1521
6	Mental Demand	-0.2343	**0.6498**
7	Mental Demand	0.0445	**0.4829**
0	Physical	0.1849	**0.8811**
1	Physical	-0.0981	**0.8726**

2	Physical	**-0.4322**	**0.8294**
3	Physical	**-0.5175**	**0.7339**
5	Physical		**0.6873**
6	Physical	-0.1723	**0.7648**
7	Physical	0.2714	**0.7097**
0	Temporal	-0.2434	**0.3608**
1	Temporal	**-0.4677**	0.2542
2	Temporal	**-0.4156**	**0.4381**
3	Temporal	**-0.6075**	**0.5969**
5	Temporal		0.2403
6	Temporal	**-0.3900**	**0.5085**
7	Temporal	0.1034	**0.6978**
0	Performance	**-0.6054**	0.0631
1	Performance	-0.0602	0.0246
2	Performance	**-0.7004**	**0.4784**
3	Performance	**-0.5077**	**0.4368**
5	Performance		-0.2163
6	Performance	**-0.5735**	**0.4938**
7	Performance	-0.2244	**0.6143**
0	Effort	-0.2149	**0.5930**
1	Effort	-0.0774	**0.6196**
2	Effort	**-0.3091**	**0.5760**
3	Effort	**-0.5664**	**0.4973**
5	Effort		0.2860
6	Effort	**-0.3234**	**0.6343**
7	Effort	-0.0566	**0.6626**
0	Frustration	**-0.4067**	-0.2129
1	Frustration	-0.1123	0.3373
2	Frustration	**-0.6695**	**0.3940**
3	Frustration	**-0.6295**	**0.6720**
5	Frustration		-0.0255
6	Frustration	**-0.5498**	**0.3862**
7	Frustration	-0.1955	**0.7254**
0	Total	-0.1143	**0.7342**
1	Total	-0.1504	**0.8288**
2	Total	**-0.4625**	**0.7178**
3	Total	**-0.6967**	**0.7242**
5	Total		0.2345
6	Total	**-0.4146**	**0.6857**
7	Total	0.0076	**0.7571**

Note: Values of $r > 0.3$ are printed in **bold type**

Results of a regression an ROC analysis are presented in Table 15. Total TLX values are significantly related to *a priori* levels of task load, and are classified as “good” detectors of task load. They are similarly significantly related to task load.

Table 15. Regression and ROC analysis: Total TLX detecting *a priori* task load and evaluator score.

Effect	Regression coefficient	Standard Error	*df*	*t*	*p*	C-statistic
High vs. Medium+Low	0.1322	0.0230	113	5.7477	<.001	0.8811
High vs. Medium	0.0860	0.0208	73	4.1370	<.001	0.8023
						-2 log likelihood
Evaluator score	-0.0178	0.0058	101	-3.0699	<.003	325.4667

7.2.2. Relationship between *a priori* task load and evaluator scores

Evaluator scores were significantly related to *a priori* ratings of task load, with task load ratings treated as a continuous variable (low = 1, medium =2, and high = 3) across all flight tasks, $t(101) = 2.86$, $p < .006$, as well as across just the tasks proposed for future research, $t(65) = 2.01$, $p < .05$. With task load treated as a categorical, the relationship was not statistically significant. The relationship to the continuous variable tended to be high, but far from perfect (r = ~0.5, indicating that *a priori* task load accounts for approximately 25% of the variance in evaluator scores). In the tables below, we will show data on the physiological relationship to evaluator score data.

7.3. Psychophysiological association with TLX total score

Total TLX scores were significantly associated with a broad array of psychophysiological measures (Tables 16 and 17), showing that higher TLX scores were related significantly, although imperfectly, with higher physiological arousal and greater ventilation. Results were very similar for all tasks vs. for tasks selected for future research. The association with total TLX score was significantly positive for heart rate (and therefore negative for R-R interval) and negative for LF and HF HRV. Higher TLX scores were related to higher heart rate and lower LF and HF HRV. (The latter two may be considered measures of parasympathetic function. Higher values are is associated with relaxation. The two values are blocked by involvement in high-intensity activity.) Higher TLX scores also were associated with higher systolic blood pressure, but not diastolic blood pressure. Higher TLX scores also were associated with higher levels of ventilation: minute volume ventilation, and related measures of respiration rate. There also was a positive association between total TLX score and inspiratory breath time/total breath time ratio, which would maximize air intake, and between total TLX score and percent of breaths that were sighs, which also would increase air intake. TLX scores also were associated with higher levels of body movement.

Table 16. Regression Analysis of Association between Physiological Measures and Total TLX Scores Data from all tasks

Physiological system	Effect	Regression Coefficient	*s.e.*	*df*	*t*	*p*
Heart rate	**Mean RRI**	**-0.085**	**0.019**	**141**	**-4.351**	**0.000**
	SDNN	0.129	0.069	141	1.865	0.064
	Minimum RRI	**-0.107**	**0.019**	**141**	**-5.725**	**0.000**
	Mean HR	**0.911**	**0.206**	**141**	**4.413**	**0.000**
	Log LF HRV	**-5.389**	**1.697**	**141**	**-3.175**	**0.002**
	Log HF HRV	**-6.071**	**1.983**	**141**	**-3.062**	**0.003**
	Log VLF HRV	0.438	1.616	141	0.271	0.787
Respiration	**Respir. Rate**	**1.099**	**0.252**	**137**	**4.368**	**0.000**
	Tidal volume	-0.001	0.000	137	-1.816	0.072
	Mean ETCO2/task	-0.296	0.848	138	-0.349	0.728
	Minimum $ETCO_2$	-1.091	0.593	138	-1.839	0.068
	Min. vol ventil.	**1.074**	**0.274**	**137**	**3.927**	**0.000**
	% sighs	**-0.354**	**0.161**	**137**	**-2.194**	**0.030**
	Insp time/total	**72.135**	**33.345**	**137**	**2.163**	**0.032**
Motion	**Accelerometer**	**16.580**	**6.938**	**137**	**2.390**	**0.018**
Blood pressure	**Systolic**	**0.456**	**0.130**	**144**	**3.514**	**0.001**
	Diastolic	-0.172	0.202	144	-0.855	0.394

Table 17. Regression Analysis of Association between Physiological Measures and Total TLX Scores, Data from tasks selected for future research

Physiological system	Effect	Regression Coefficient	*s.e.*	*df*	*t*	*p*
HR	**Mean RRI**	**-0.103**	**0.024**	**92**	**-4.379**	**0.000**
	SDNN	0.125	0.079	92	1.580	0.118
	Minimum RRI	**-0.120**	**0.021**	**92**	**-5.778**	**0.000**
	Mean HR	**1.037**	**0.245**	**92**	**4.242**	**0.000**
	Log LF HRV	**-5.692**	**2.060**	**92**	**-2.763**	**0.007**
	Log HF HRV	**-6.312**	**2.299**	**92**	**-2.746**	**0.007**
	Log VLF HRV	1.924	1.949	92	0.987	0.326
Respiration	**Respir. Rate**	**1.397**	**0.272**	**90**	**5.134**	**0.000**
	Tidal volume	-0.001	0.000	90	-1.825	0.071
	Mean ETCO2/task	0.168	0.941	91	0.179	0.858
	Minimum $ETCO_2$	-0.913	0.676	91	-1.351	0.180
	Min. vol ventil.	**1.036**	**0.315**	**90**	**3.286**	**0.001**
	% sighs	-0.297	0.174	90	-1.714	0.090
	Insp time/total	**94.602**	**35.296**	**90**	**2.680**	**0.009**
Motion	**Accelerometer**	**34.861**	**10.387**	**90**	**3.356**	**0.001**
Blood pressure	**Systolic**	**0.509**	**0.142**	**95**	**3.582**	**0.001**
	Diastolic	-0.121	0.231	95	-0.522	0.603

7.4. Relationship between TLX scales and blood pressure.

For diastolic BP, within-subject correlations with TLX variables tended to be moderate and negative (higher diastolic BP with lower load), except Subject #5, who showed the opposite pattern. This was the subject with the greatest experience with the tasks and with the flight simulator. There was a similar but lesser tendency in Subject 6. Similarly, correlations between diastolic BP and evaluator scores tended to be positive (higher diastolic BP with better performance), with the exception of Subject 7. However, as indicated above, the over-all linear relationship was not significant. These data reflect different patterns among subjects (Table 18). For systolic BP, correlations with TLX scores tended to be moderately positive (higher systolic BP with higher load), except for Subject 0, who was the least experienced with the B737 environment, where the correlations were negative. Correlation with evaluator scores tended to be moderately negative (higher systolic BP with poorer performance), except for Subject 000, where the correlation was positive. The correlation between systolic BP and *a priori* task load tended also to be positive, but low.

Table 18. Correlations between Blood Pressure, TLX scales, and evaluator score

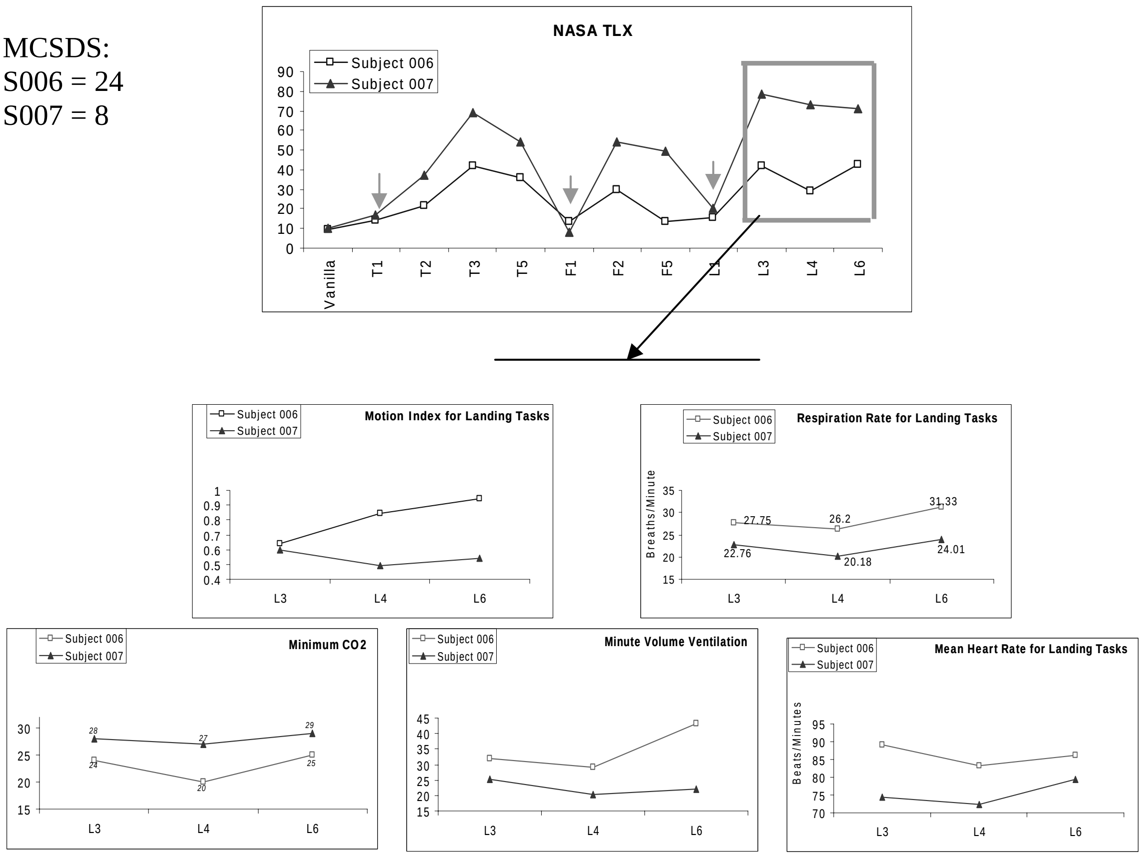
		NASA TLX Scales								
Sub #	Variable	Mental	Physical	Temporal	Perform-Ance	Effort	Frustration	Total	Load	Evaluator Score
0	BP Diastol	-0.0492	-0.0784	-0.0859	**-0.3481**	-0.1922	0.0377	-0.1503	-0.0739	0.1353
1	BP Diastol	**-0.3459**	**-0.3832**	**0.3361**	-0.1949	-0.0914	-0.1558	**-0.3705**	**-0.3594**	0.0598
2	BP Diastol	**-0.3943**	**-0.3043**	-0.2611	**-0.6211**	-0.1661	**-0.3871**	**-0.3941**	-0.2952	**0.4541**
3	BP Diastol	**-0.5551**	**-0.5107**	-0.2694	0.0710	-0.2493	**-0.3411**	**-0.3726**	**-0.5463**	**0.4709**
5	BP Diastol	**0.4217**	**0.5475**	**0.6614**	**0.4160**	**0.4757**	**0.3333**	**0.6857**	**0.3455**	.
6	BP Diastol	0.2700	**0.3057**	0.2115	0.1944	0.1894	-0.2188	0.2252	-0.1347	**0.3728**
7	BP Diastol	0.2392	-0.0253	0.0411	**0.5212**	0.1452	0.2009	0.1884	0.1501	**-0.4678**
0	BP Systol	-0.0377	0.1106	**-0.3236**	**-0.4758**	0.0686	**-0.4589**	-0.0716	-0.0162	**0.5158**
1	BP Systol	**0.4171**	**0.4569**	0.2334	0.1817	**0.6533**	**0.4069**	**0.4552**	**0.3138**	0.1090
2	BP Systol	-0.0604	**0.3426**	**0.5099**	**0.3170**	0.2772	**0.4918**	0.2757	0.1785	**-0.5432**
3	BP Systol	0.2501	0.1427	**0.3296**	0.1753	0.1263	0.1570	0.2421	0.2319	**-0.3138**
5	BP Systol	**0.6266**	**0.7215**	**0.7146**	0.1544	**0.6822**	**0.4405**	**0.7557**	**0.6183**	.
6	BP Systol	0.0356	0.1852	**0.3007**	0.1947	0.1777	**0.3055**	0.2154	0.2903	**-0.3161**
7	BP Systol	**0.3230**	**0.5479**	**0.4818**	**0.3737**	**0.3996**	0.2668	**0.4680**	**0.3613**	0.0041

7.6. Discrepancies between TLX values and physiological data: the role of defensiveness

Consistent with the large amount of data showing poor relationships among physiological and self-report indices of stress (Boone et al, 1999; Lehrer & Woolfolk, 1993), we show TLX and physiological responses from two subjects below (Fig 22). One of these subjects showed high reactivity on the TLX, but another very low TLX reactivity but high physiological reactivity to flight tasks. We note that the individual with low TLX and high physiological reactivity also scored high on the Marlowe-Crowne Social Desirability Scale (MCSDS) (Crowne & Marlowe, 1960), a paper-and-pencil measure that reflects the psychological trait of defensiveness. Other research with this instrument has found that individuals scoring high on it tend to show a very similar response: low scores on paper-and-pencil measures of emotional reactivity, but high physiological reactivity to stressful stimuli (Weinberger et al, 1979). However, when added to the statistical model, MCSDS scores contributed little to the statistical relationship between physiological or TLX data and *a priori* task difficulty. However, this study has very low power for examining between-subjects relationships such as this.

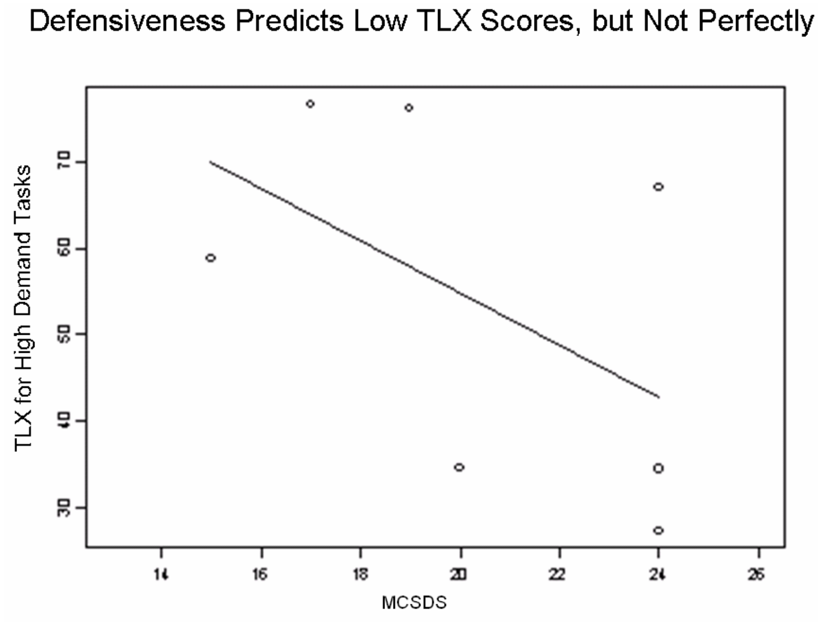
Fig 22. Discrepancies between TLX and physiological assessment in subjects high and low in defensiveness

MCSDS:
S006 = 24
S007 = 8



Consistent with previous research, in the current study (Fig 23) we see a small negative relationship between total TLX scores and scores on the MCSDS. Defensive subjects tended to give lower workload ratings on the TLX. Note that MCSDS scores for most of our subjects tend to be relatively high. Previous literature tends to classify scores higher than 17-19 as high (Brown et al, 1996; Helmers et al, 1995; King et al, 1990; Niaura et al, 1994; Shapiro et al, 1993; Weinberger et al, 1979; Warrenburg et al, 1989). All of our subjects except one scored above this level. If this represents the typical pattern among airline pilots, it would suggest that physiological assessment may be more sensitive than self-report assessment as a measure of workload in this population. For high-load tasks, the correlation coefficient is -.53. The correlation coefficient is not significant in this context because of the low number of subjects, but suggests that further research may show a consistent relationship.

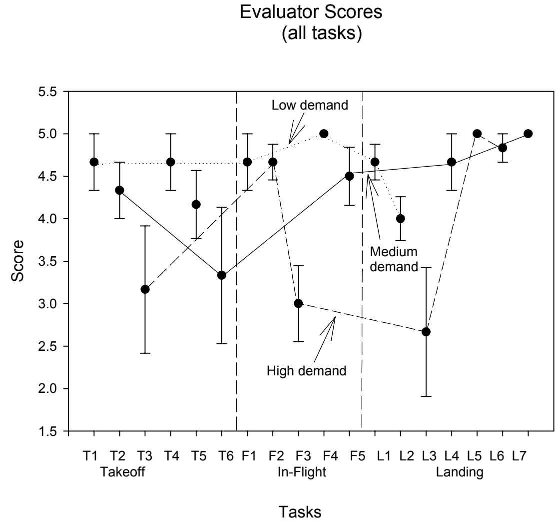
Fig 23.



8. Evaluator scores of pilot performance

The modal score on this measure was perfect (5 out of 5), with particularly little variance for low-demand tasks, where almost all values were 4 or 5. However, there was more differentiation among tasks with higher loads, where task performance scores were roughly related to *a priori* ratings of load (Fig. 24). Subjects tended to score lowest on three *a priori* high-demand tasks (T3 [wind shear], F3 [rapid depressurization], and L3 [elevator jam]), and one *a priori* medium demand task (T6, loss of brakes), but with some inconsistencies: Evaluator scores tended to be high for three high-demand tasks, F2 (wake turbulence during descent at 8000 feet), L5 (wake turbulence during landing), and L6 (landing with one landing gear stuck up). With these exceptions, there was no overlap between high- and low demand tasks in evaluator scores. Evaluator scores also tended to be closer to those for medium-demand tasks for one low-demand task, L2 (instrument landing).

Fig 24



8.1. Relationship between pilot performance (evaluator scores) and TLX

The linear relationship between the total TLX scale and evaluator scores was negative and highly significant (Table 19 in next section and Section 7.2.2 and Table 13 above). Higher perception of task load was related to poorer performance as assessed by evaluator scores.

8.2. Effect of including the Marlowe-Crowne Social Desirability Scale (a measure of defensiveness) in analyses of pilot performance

We examined the effect of including the Marlowe-Crowne Social Desirability Scale in some of the analyses below because, in previous research, this scale is associated with suppression of self-report of symptoms (Contrada et al, 1997a,b; Newton & Contrada, 1992; Shapiro et al, 1995). We found, however, that our results were not generally affected by this correction. Table 19 shows the added effect of including this scale in the analysis of the relationship between TLX values and evaluator scores. The effect of adding this variable to analyses of physiological data was similarly small. Some individual differences did show strong relationships with this scale, however.

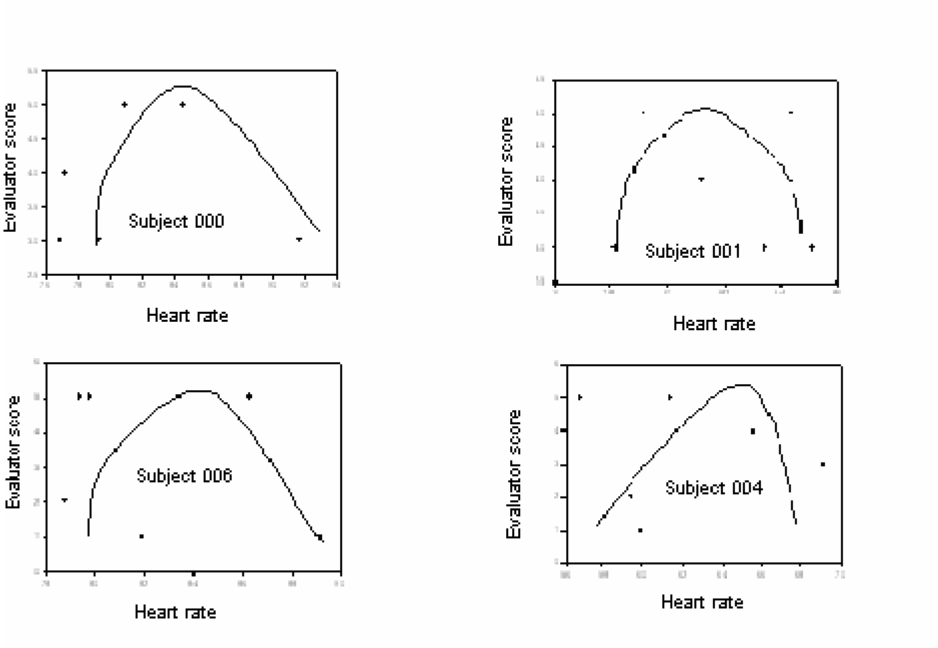
Table 19. Significance of relationship between evaluator scores and total TLX

Mixed models analysis	Regression Coefficient	*s.e.*	*df*	*t*	*P*
Including MCSDS in the model	-0.018	0.006	103	-3.097	0.003
Not including MCSDS in the model	-0.017	0.006	103	-3.001	0.003

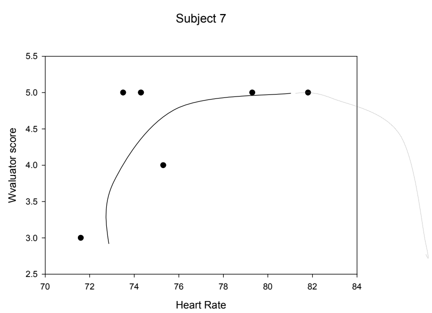
8.3. Relationship between evaluator score and heart rate.

There appears to be a curvilinear relationship between task load and heart rate. Within subjects, moderately high levels of HR tended to correlate with the highest performance ratings. This is consistent with the well known “Yerkes-Dodson curve”: an inverted U-function between arousal (stress), often measured by heart rate, and task performance on medium load tasks. Data are presented in Fig 25 for five of the seven subjects. The other two subjects did not show sufficient variance in performance scores to plot such a function. Although data for Subject 7 appears to show only a positive relationship between evaluator scores and heart rate, it is possible that the heart rate level at which performance deteriorates did not occur in this experiment for this subject. The subject appeared to have a higher than usual behavioral tolerance for high physiological arousal, as evidenced by heart rate.

Fig 25. Relationship between Heart Rate and Performance Rating



This subject appeared to have a particularly high resistance to stress effects



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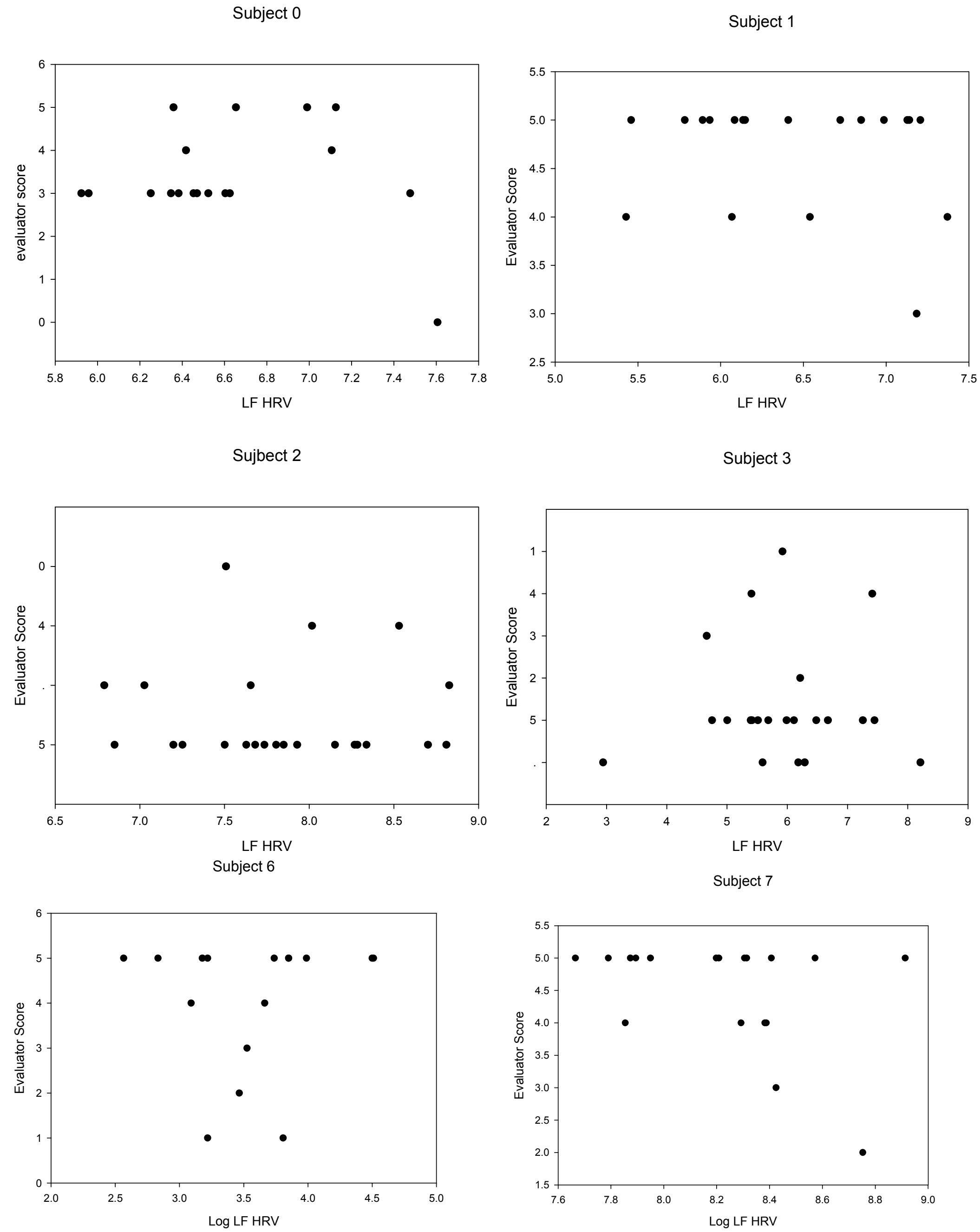
Despite the curvilinear relationship, a significant negative linear relationship was found between heart rate and evaluator scores, Regression Coefficient=-0.15, s.e. = -.006, *df* = 99, *t* = -2.438, *p* < .02. Higher heart rates were related to poorer performance, as estimated by evaluator scores.

8.3.1. Relationship between HRV and performance

8.3.1.1. LF HRV

Fig 26 shows a tendency to higher performance with a moderate level of LF HRV in Subjects 2 and 3, perhaps a curvilinear relationship. Higher performance occurred at a lower level of LF HRV in Subjects 0, 1, and 7, and at high and low LF HRV in Subject 6. A mixed models analysis found no significant linear relationship between LF HRV and evaluator scores.

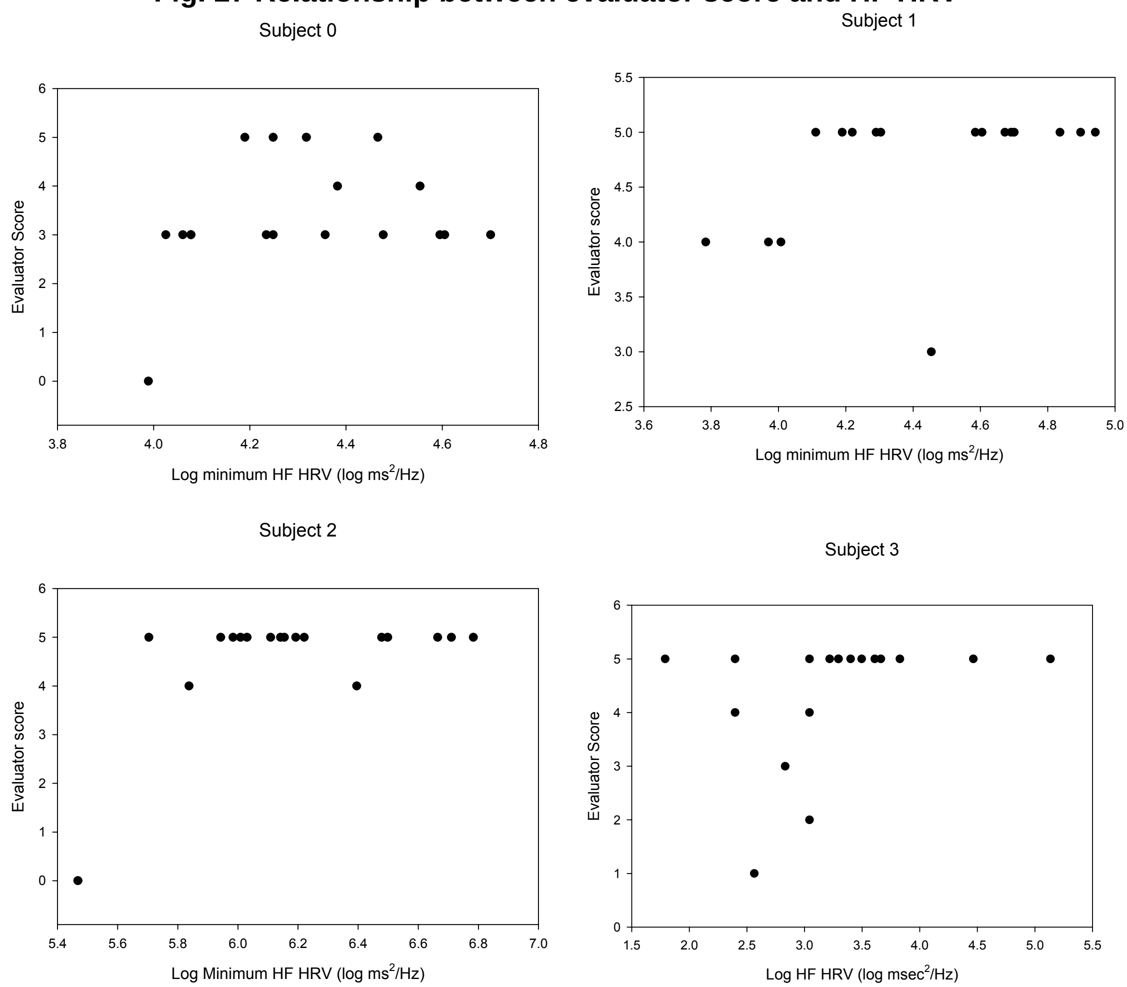
Fig 26. Relationship between Log Low Frequency HRV by Evaluator Score for Individual Subjects



8.3.1.2. HF HRV

With the exception of Subject 7 (Fig 27), all subjects show lower evaluator scores at the lowest level of HF HRV, and a tendency toward lower HF HRV may be seen with lower evaluator scores in this figure. The mixed models analysis found a borderline significant positive relationship between HF HRV and evaluator scores (Table 20). Poorer performance appeared to correlate with parasympathetic inhibition.

Fig. 27 Relationship between evaluator score and HF HRV



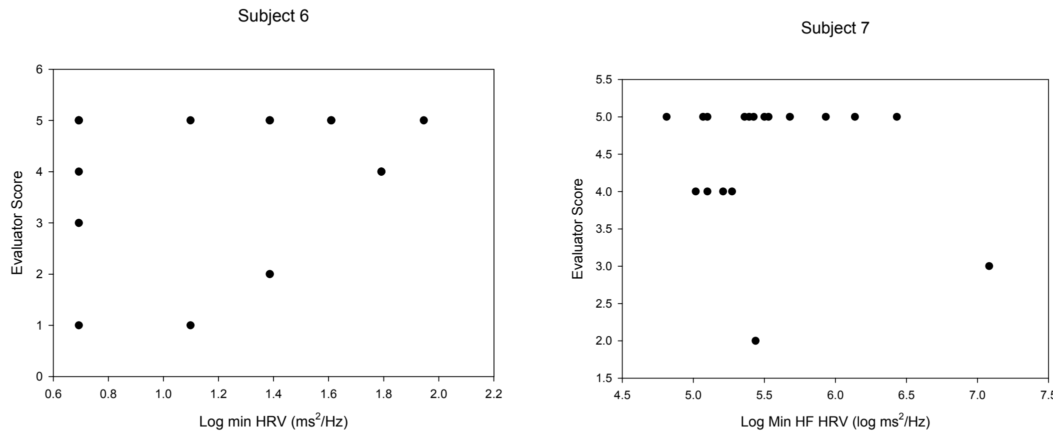


Table 20. Mixed Models Analysis of Relationship Between log HF HRV and Evaluator Scores

Tasks	Regression Coefficient	*s.e.*	*df*	*t*	*p*
All tasks	**0.179**	**0.104**	**99**	**1.719**	**0.089**
Selected tasks	**0.243**	**0.132**	**61**	**1.835**	**0.071**

8.3.1.3. Standard deviation of normal R-R intervals (SDNN)

SDNN is a measure of total heart rate variability. In this study, it was related to heart rate responsivity to "events" in tasks, causing major within-task cardiac accelerations. Among all tasks, there was a significant negative correlation between SDNN and evaluator score, with lower SDNN related to better performance, as assessed by the evaluator score. However, this relationship disappeared among tasks selected for future research. The relationship appears to reflect smaller HR accelerations during "events" in tasks where subjects performed better (Table 21).

Table 21. Mixed Models Analysis of Relationship Between SDNN and Evaluator Scores

Tasks	Regression Coefficient	*s.e.*	df	*t*	*p*
All tasks	**-0.012**	**0.005**	**99**	**-2.418**	**0.017**
Selected tasks	-0.008	0.006	61	-1.416	0.162

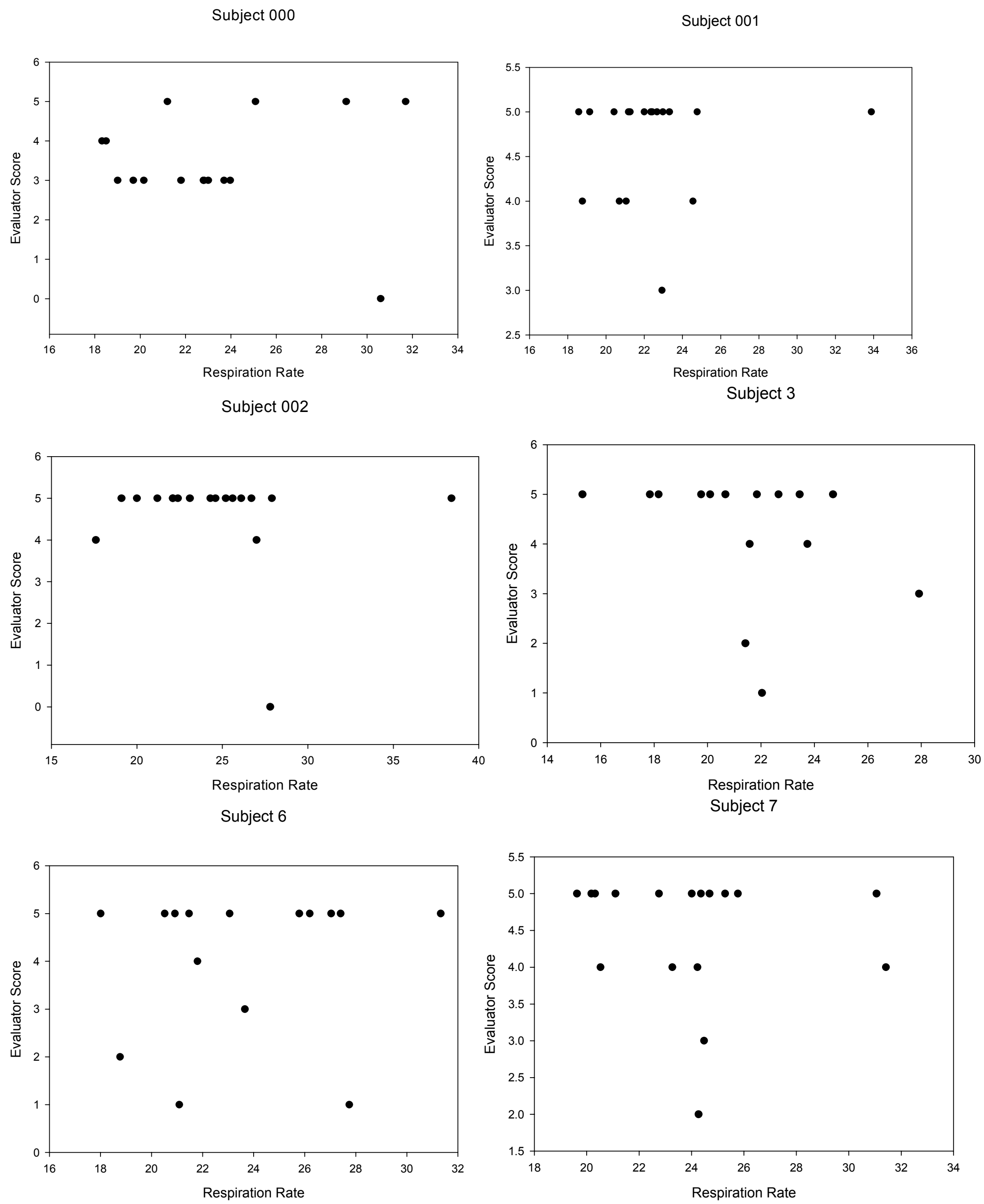
Data in bold reflect significant findings

8.4. Relationship between evaluator scores and ventilation

8.4.1. Respiration rate.

For respiration rate, there was no clear pattern within subjects in the relationship with evaluator scores (Fig 28), and no significant relationship between respiration rate and evaluator scores. However Fig 28 suggests that moderately higher respiration rates may be associated with poorer performance, suggesting a curvilinear relationship.

Fig 28. Relationship between Respiration Rate and Evaluator Scores for Individual Subjects



8.4.2. Minute volume ventilation.

Minute volume ventilation does not show a clear overall pattern of association with evaluator scores, but, in several subjects (Table 22) minute volume ventilation was negatively associated with evaluator scores, suggesting that greater ventilation was associated with poorer performance...

8.4.3. End-tidal carbon dioxide ($ETCO_2$).

Although hypocapnia was common during the moments of highest demand during the various flight tasks it appeared that, across subjects, there were more incidents of poorer performance when subjects hyperventilated than at other times. We graphed performance scores by the minimum $ETCO_2$ during each task. Note that most subjects were in the hypocapnia zone at their lowest level during each task, for most tasks (Fig 29), indicating that healthy people do tend to show $ETCO_2$ levels in this zone, at least momentarily, while engaging in tasks requiring physical and mental effort. Incidences of evaluator score ≤ 2 all occurred when subjects were in the hypocapnia zone. *In all cases,* the task for each subject with the lowest evaluator score was accompanied by a task-minimum $ETCO_2$ value of <32 mm Hg, the level at which physiological effects of hypocapnia occur, such as decreased brain blood flow. For three of six subjects, the tasks with the lowest evaluator score showed minimum $ETCO_2$ readings below the subject's median. For two subjects the value was at the median, and for one it was above, showing that not all people respond to high-load tasks with decreases in $ETCO_2$, although most do seem to show this pattern. Nevertheless, there was no overall linear relationship between $ETCO_2$ and evaluator scores.

Fig 29.

Evaluator Score by Minimum $ETCO_2$ in Task

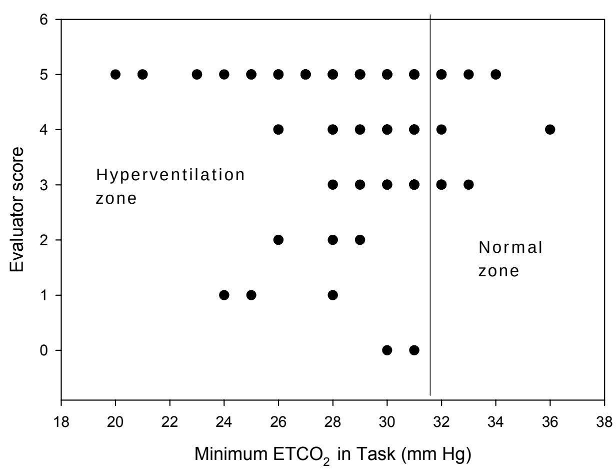


Table 22. Correlations: TLX Self-Ratings, *A Priori* Task load Rating, and Evaluator Performance Score with Other Respiratory Variables in Each Task

		NASA TLX scales								
S#	Variable	Mental	Phys-ical	Temp-oral	Perfor-mance	Effort	Frust-ration	Total	Load	Eval Score
0	Min Vol Vent	0.0238	-0.0062	-0.2754	0.2399	-0.1127	0.1751	0.0430	0.2344	0.2914
1	Min Vol Vent	0.0449	**0.4288**	0.0091	**0.4119**	0.2480	0.2169	0.2682	0.1453	-0.1619
2	Min Vol Vent	**0.4106**	**0.5018**	0.1301	**0.4361**	0.2879	**0.3644**	**0.4051**	**0.3982**	**-0.7467**
3	Min Vol Vent	0.2115	**0.6848**	**0.4111**	**0.5367**	0.2461	**0.3831**	**0.5317**	**0.4893**	-0.0267
5	Min Vol Vent	**0.3421**	**0.5158**	**0.2629**	**-0.5153**	**0.3822**	**0.5206**	0.2328	**0.6425**	.
6	Min Vol Vent	**0.7383**	**0.7150**	**0.3972**	**0.3186**	**0.6636**	0.0980	**0.6133**	**0.4743**	0.1556
7	Min Vol Vent	0.1906	**0.4727**	**0.3985**	0.2598	**0.4341**	0.2958	**0.3925**	**0.4466**	-0.1207
0	Respir Rate	0.2769	0.0723	-0.2257	**0.3205**	0.0538	-0.0366	0.1931	0.1276	-0.0485
1	Respir Rate	**0.3714**	0.2730	0.2153	0.1839	0.2246	0.2058	**0.3393**	0.1579	.0938
2	Respir Rate	0.1506	0.1005	-0.0881	0.2493	0.1202	0.1272	0.1878	0.2377	-0.1272
3	Respir Rate	**0.4545**	**0.4567**	**0.4008**	**0.4682**	**0.3794**	0.2849	**0.5073**	0.2906	**-0.3426**
5	Respir Rate	**0.5804**	**0.3359**	**0.4823**	-0.0702	0.0916	**0.4312**	**0.3315**	**0.4891**	
6	Respir Rate	**0.6926**	**0.6822**	**.4480**	**0.4253**	**0.6445**	0.1066	**0.6250**	**0.4539**	0.1245
7	Respir Rate	**0.3806**	0.2337	**0.4831**	**0.3551**	**0.3650**	**0.4206**	**0.4178**	**0.4042**	-0.1607

Note: Values of $r > 0.3$ are printed in **bold type.**

9. Incremental prediction of task load and performance using physiological measures combined with self-report measures of workload (the TLX) compared with self-report measures alone: Statistical approach.

These analyses were done in order to evaluate the *additive* predictability performance from physiological measures over a method that is less expensive and easier to use, i.e., a well-validated self-report measure, NASA's TLX scale. In these analyses, we assumed that physiological measures would only be of interest in evaluating flight task load if they added predictability of performance. Analyses of TLX subscales showed the same pattern as described below for TLX total score. None of the subscales, when substituted for Total score, eliminated the effect of physiological variables.

9.1. Heart rate measures

In the first series of analyses, we examined the prediction of *a priori* task load using all flight tasks, with *a priori* values treated as a continuous variable. We found a significant contribution ($t(130) = 3.50$, $p < .001$) for the *s.d.* of cardiac interbeat intervals and for the minimum heart rate during each task ($t(130) = 3.54$, $p < .001$) for residual prediction after effects of TLX prediction are taken out. Higher-load tasks were characterized by greater heart rate variability and a faster heartbeat. The greater heart rate variability was not reflected in either LF or HF HRV values, indicating that it reflected the large shifts in heart rate occurring during stressful events within the higher-load tasks. A similar pattern of results were found only for tasks chosen for future research.

In ROC analyses detecting *a priori* task load from combined physiological measures and TLX scores, adding SDNN to the model increased the C statistic. For differentiating between High vs. combined

Medium and Low load tasks, the improvement was from the “good” to the “excellent” range controlling for the Vanilla or Breathing baselines, but did not change categories of C for other comparisons (Table 23). However, there were a number of *statistically significant* differences between task load difficulties and *various* cardiac measures after controlling for the effects of TLX scores. These differences appeared in SDNN, the minimum RRI in each task, and for the LF:HF HRV ratio controlling only for the breathing task. The C statistic indicated an increase to “excellent” detector of High vs. combined Medium and Low load tasks, over the TLX. Without controlling for baseline, and for differences between High and Medium load tasks, only the effects for SDNN and minimum RRI were significant, but there were no differences in level of the C statistic.

TABLE 23a. Added Contribution of Physiological Measures Over Total TLX for Discriminating High from combined Medium + Low load tasks: Deviation from baseline Vanilla task. All flight tasks.

						C-statistic	
Effect	Regression coefficient	Standard error	*df*	*t*	*p*	TLX + Physio	TLX alone
TLX alone	0.1322	0.0230	113	5.7477	<.001	0.8811	0.8811
CARDIAC MEASURES							
Mean RRI/task	-0.0044	0.0047	109	-0.9358	0.3515	0.8801	0.8811
S.D. RRI (SDNN)	0.0479	0.0174	109	2.7477	0.0070	0.9012	0.8811
Min RRI/task	-0.0135	0.0052	109	-2.5878	0.0110	0.8901	0.8811
Mean HR	0.0539	0.0499	109	1.0808	0.2822	0.8792	0.8811
LF HRV	0.0003	0.0003	109	1.3592	0.1769	0.8898	0.8811
HF HRV	0.0008	0.0011	109	0.7497	0.4550	0.8827	0.8811
Log LF HRV	0.7126	0.4037	109	1.7651	0.0803	0.8936	0.8811
Log HF HRV	0.4077	0.4261	109	0.9567	0.3408	0.8870	0.8811
Log VLF HRV	0.4994	0.3164	109	1.5786	0.1173	0.8847	0.8811
LF:HF HRV ratio	0.0005	0.0008	109	0.5877	0.5579	0.8807	0.8811
Normalized HF HRV	-5.7744	3.8430	109	-1.5026	0.1358	0.8850	0.8811
Normalized LF HRV	5.5183	3.7042	109	1.4898	0.1392	0.8853	0.8811
Ventric. systole time	-0.0118	0.0127	110	-0.9289	0.3550	0.8563	0.8811
Ventric. relax. Time	-0.0303	0.0262	110	-1.1550	0.2506	0.8604	0.8811
Heart muscle condt’n	0.3989	0.3944	110	1.0115	0.3140	0.8606	0.8811
Cardiac economics	-0.0156	0.1312	110	-0.1190	0.9055	0.8586	0.8811
Ventric relax % RRI	-0.2625	0.2483	110	-1.0574	0.2926	0.8629	0.8811
Systole % RRI	0.1017	0.1812	110	0.5614	0.5757	0.8557	0.8811
BLOOD PRESSURE							
Systolic BP	0.0372	0.0289	112	1.2878	0.2005	0.8791	0.8811
Diastolic BP	-0.0579	0.0402	112	-1.4410	0.1524	0.8903	0.8811
RESPIRATION MEASURES							
Respiration rate	0.0285	0.0769	92	0.3703	0.7120	0.7742	0.8811
Min vol ventilation	0.0684	0.0602	92	1.1360	0.2589	-0.1023	0.8811
Mean ETCO2/task	-0.3878	0.2489	92	-1.5578	0.1227	0.7760	0.8811
Min ETCO2/task	-0.0013	0.1051	92	-0.0120	0.9905	0.7724	0.8811
% sighs	0.0782	0.0482	92	1.6232	0.1080	0.7803	0.8811
MOVEMENT							
Motion sensor	3.0463	1.6453	92	1.8515	0.0673	0.7788	0.8811

TABLE 23b. Added Contribution of Physiological Measures Over Total TLX for Discriminating High load from combined Medium + Low load tasks: Deviation from baseline Counting task, all flight tasks

Effect	Regression coefficient	Standard error	*df*	*t*	*p*	C-statistic TLX + Physio	C-statistic TLX alone
Mean RRI/task	-0.0020	0.0050	109	-0.3375	0.7364	0.8815	0.8811
S.D. RRI (SDNN)c	0.0493	0.0182	109	2.7133	0.0077	0.8995	0.8811
Min RRI/task	-0.0124	0.0054	109	-2.3058	0.0230	0.8939	0.8811
Mean HR	0.0306	0.0515	109	0.5937	0.5540	0.8815	0.8811
LF HRV	0.0004	0.0003	109	1.5151	0.1326	0.8878	0.8811
HF HRV	0.0009	0.0011	109	0.7689	0.4436	0.8827	0.8811
log LF HRV	0.7286	0.4213	109	1.7297	0.0865	0.8933	0.8811
log HF HRV	0.3929	0.4251	109	0.9244	0.3573	0.8855	0.8811
log VLF HRV	0.4391	0.3293	109	1.3332	0.1853	0.8835	0.8811
LF:HF HRV ratio	0.0005	0.0008	109	0.5660	0.5725	0.8807	0.8811
Normalized HF HRV	-5.4532	4.0208	109	-1.3563	0.1778	0.8850	0.8811
Normalized LF HRV	5.0970	3.8450	109	1.3256	0.1877	0.8844	0.8811
Ventric. systole time	-0.0025	0.0130	110	-0.1917	0.8483	0.8583	0.8811
Ventric. Relax. time	-0.0283	0.0265	110	-1.0673	0.2882	0.8599	0.8811
Heart muscle condt'n	0.3464	0.3802	110	0.9111	0.3642	0.8600	0.8811
Cardiac economics	-0.0215	0.1356	110	-0.1586	0.8743	0.8589	0.8811
Ventric relax % RRI	-0.2777	0.2489	110	-1.1160	0.2668	0.8623	0.8811
Systole % RRI	0.0292	0.1857	110	0.1574	0.8752	0.8577	0.8811
Systolic BP	0.0203	0.0291	112	0.6996	0.4857	0.8794	0.8811
Diastolic BP	-0.0560	0.0393	112	-1.4242	0.1572	0.8908	0.8811
RESPIRATION VARIABLES							
Respiration rate	-0.0010	0.0818	97	-0.0118	0.9906	0.8044	0.8811
Min vol ventilation	0.0502	0.0680	97	0.7376	0.4625	0.8032	0.8811
Mean ETCO2/task	-0.1715	0.2101	109	-0.8160	0.4163	0.8829	0.8811
Min ETCO2/task	-0.0183	0.1026	109	-0.1781	0.8590	0.8799	0.8811
% sighs	0.0351	0.0532	97	0.6597	0.5110	0.8083	0.8811
MOVEMENT							
Motion sensor	2.4259	1.6711	97	1.4517	0.1498	0.8075	0.8811

TABLE 23c. Added Contribution of Physiological Measures Over Total TLX for Discriminating High load from combined Medium + Low load tasks: Deviation from baseline Breathing task, all flight tasks

Effect	Regression Coefficient	Standard error	*df*	*t*	*p*	C-statistic TLX + Physio	C-statistic TLX alone
Mean RRI/task	-0.0039	0.0048	109	-0.8010	0.4197	0.8807	0.8811
S.D. RRI (SDNN)	0.0496	0.0169	109	2.9335	0.0041	0.9000	0.8811
Min RRI/task	-0.0130	0.0052	109	-2.493	0.0142	0.8921	0.8811
Mean HR	0.0514	0.0496	109	1.0347	0.3031	0.8795	0.8811
LF HRV	0.0003	0.0002	109	1.7065	0.0908	0.8878	0.8811
HF HRV	0.0009	0.0011	109	0.7767	0.4390	0.8832	0.8811
log LF HRV	0.8430	0.4243	109	1.9870	0.0494	0.8921	0.8811
log HF HRV	0.3741	0.4255	109	0.8793	0.3812	0.8864	0.8811
log VLF HRV	0.4628	0.3310	109	1.3981	0.1649	0.8832	0.8811
LF:HF HRV ratio	0.0016	0.0007	109	2.3592	0.0201	0.8755	0.8811
Normalized HF HRV	-6.2286	4.1801	109	-1.4900	0.1391	0.8841	0.8811
Normalized LF HRV	5.9540	4.0024	109	1.4876	0.1397	0.8850	0.8811
Ventric. systole time	-0.0074	0.0129	110	-0.5718	0.5686	0.8592	0.8811
Ventric. relax. time	-0.0317	0.0259	110	-1.2250	0.2232	0.8602	0.8811
Heart muscle condt'n	0.4128	0.3929	110	1.0506	0.2958	0.8609	0.8811
Cardiac economics	0.0110	0.1325	110	0.0833	0.9338	0.8577	0.8811
Ventric relax % RRI	-0.2901	0.2480	110	-1.1697	0.2446	0.8620	0.8811
Systole % RRI	0.0971	0.1805	110	0.5381	0.5916	0.8600	0.8811
Systolic BP	0.0246	0.0286	112	0.8587	0.3923	0.8785	0.8811
Diastolic BP	-0.0530	0.0399	112	-1.3278	0.1869	0.8894	0.8811
Respiration rate	0.0318	0.077	109	0.4147	0.6792	0.8801	0.8811
Min vol ventilation	0.0717	0.0599	109	1.1981	0.2334	0.8818	0.8811
Mean ETCO2/task	-0.1702	0.1723	109	-0.9880	0.3253	0.8821	0.8811
Min ETCO2/task	0.0062	0.0992	109	0.0622	0.9505	0.8820	0.8811
% sighs	0.0186	0.0302	109	0.6171	0.5384	0.8855	0.8811
MOVEMENT							
Motion sensor	3.0317	1.4770	109	2.0526	0.0425	0.8876	0.8811

TABLE 23d. Added Contribution of Physiological Measures Over Total TLX for Discriminating High load from Medium load tasks: Deviation from baseline Vanilla task. All flight tasks.

Effect	Regression Coefficient	Standard error	*df*	*t*	*p*	C-statistic TLX + Physio	C-statistic TLX alone
Mean RRI/task	-0.0030	0.0039	70	-0.7597	0.4500	0.7866	0.8022
S.D. RRI (SDNN)	0.0423	0.0158	70	2.6734	0.0093	0.8333	0.8023
Min RRI/task	-0.0103	0.0044	70	-2.3713	0.0205	0.8011	0.8023
Mean HR	0.0416	0.0395	70	1.0522	0.2963	0.7779	0.8023
LF HRV	0.0003	0.0002	70	1.1279	0.2632	0.8133	0.8023
HF HRV	0.0014	0.0013	70	1.0641	0.2909	0.8075	0.8023
log LF HRV	0.7117	0.3948	70	1.8025	0.0758	0.8359	0.8023
log HF HRV	0.4744	0.4163	70	1.1396	0.2584	0.8220	0.8023
log VLF HRV	0.4579	0.2819	70	1.6246	0.1087	0.8028	0.8023
LF:HF HRV ratio	0.0001	0.0008	70	0.1841	0.8544	0.8017	0.8023
Normalized HF HRV	-5.1048	3.3603	70	-1.5192	0.1333	0.8011	0.8023
Normalized LF HRV	4.8826	3.2792	70	1.4890	0.1410	0.7999	0.8023
Ventric. systole time	-0.0123	0.0107	71	-1.1509	0.2536	0.7573	0.8023
Ventric. relax. time	-0.0223	0.0234	71	-0.9520	0.3441	0.7715	0.8023
Heart muscle condt’n	0.3170	0.3867	71	0.8199	0.4150	0.7747	0.8023
Cardiac economics	-0.0843	0.1335	71	-0.6314	0.5298	0.7846	0.8023
Ventric relax % RRI	-0.2428	0.2353	71	-1.0321	0.3055	0.7857	0.8023
Systole % RRI	0.0005	0.1714	71	0.0032	0.9975	0.7787	0.8023
Systolic BP	0.0419	0.0250	72	1.6729	0.0987	0.7692	0.8023
Diastolic BP	-0.0428	0.0380	72	-1.1257	0.2640	0.8168	0.8023
Respiration rate	0.0501	0.0754	59	0.6640	0.5093	0.7053	0.8023
Min vol ventilation	0.0546	0.0480	59	1.1362	0.2604	0.7076	0.8023
Mean ETCO2/task	-0.2452	0.2369	59	-1.0351	0.3049	0.7006	0.8023
Min ETCO2/task	0.0524	0.1044	59	0.5023	0.6173	0.7207	0.8023
% sighs	0.0612	0.0413	59	1.4829	0.1434	0.7163	0.8023
MOVEMENT							
Motion sensor	8.6995	2.7108	59	3.2092	0.0022	0.7059	0.8023

TABLE 23e. Added Contribution of Physiological Measures Over Total TLX for Discriminating High load from Medium load tasks: Deviation from baseline Counting task, all flight tasks

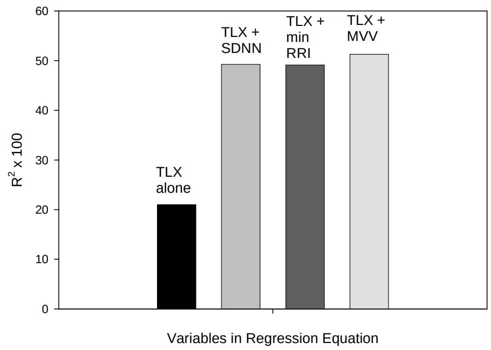
Effect	Regression Coefficient	Standard error	*df*	*t*	*p*	C-statistic TLX + Physio	C-statistic TLX alone
Mean RRI/task	0.0010	0.0047	70	0.2144	0.8308	0.8040	0.8811
S.D. RRI (SDNN)	0.0451	0.0168	70	2.6749	0.0093	0.8287	0.8811
Min RRI/task	-0.0095	0.0048	70	-1.9937	0.0501	0.8046	0.8811
Mean HR	0.0103	0.0462	70	0.2219	0.8250	0.7994	0.8811
LF HRV	0.0003	0.0002	70	1.3794	0.1722	0.8005	0.8811
HF HRV	0.0014	0.0013	70	1.1140	0.2691	0.8046	0.8811
Log LF HRV	0.7632	0.4282	70	1.7822	0.0791	0.8301	0.8811
Log HF HRV	0.4541	0.4133	70	1.0987	0.2757	0.8203	0.8811
Log VLF HRV	0.4009	0.3100	70	1.2930	0.2003	0.8023	0.8811
LF:HF HRV ratio	0.0001	0.0008	70	0.1578	0.8751	0.8023	0.8811
Normalized HF HRV	-4.9401	3.6994	70	-1.3358	0.1861	0.8005	0.8811
Normalized LF HRV	4.5479	3.5759	70	1.2718	0.2076	0.8023	0.8811
Ventric. systole time	0.0010	0.0047	70	0.2144	0.8308	0.8040	0.8811
Ventric. relax. time	0.0451	0.0168	70	2.6749	0.0093	0.8287	0.8811
Heart muscle condt'n	-0.0095	0.0048	70	-1.9937	0.0501	0.8046	0.8811
Cardiac economics	0.0750	0.0397	70	1.8905	0.0628	0.8246	0.8811
Ventric relax % RRI	0.0102	0.0462	70	0.2219	0.8250	0.7994	0.8811
Systole % RRI	0.0003	0.0002	70	1.3794	0.1722	0.8005	0.8811
Systolic BP	0.0157	0.0272	72	0.5759	0.5665	0.8011	0.8811
Diastolic BP	-0.0394	0.0366	72	-1.0779	0.2847	0.8174	0.8811
Respiration rate	-0.0003	0.0841	62	-0.0040	0.9968	0.7462	0.8811
Min vol ventilation	0.0491	0.0622	62	0.7906	0.4322	0.7468	0.8811
Mean ETCO2/task	-0.0822	0.1924	70	-0.4271	0.6706	0.7982	0.8811
Min ETCO2/task	0.0308	0.1013	70	0.3040	0.7623	0.8020	0.8811
% sighs	0.0247	0.0545	62	0.4534	0.6518	0.7520	0.8811
MOVEMENT							
Motion sensor	7.5436	2.8940	62	2.6067	0.0114	0.7573	0.8811

TABLE 23f. Added Contribution of Physiological Measures Over Total TLX for Discriminating High load from Medium load tasks: Deviation from baseline Breathing task, all flight tasks

Effect	Regression Coefficient	Standard error	*df*	*t*	*p*	C-statistic TLX + Physio	C-statistic TLX alone
Mean RRI/task	-0.0022	0.0041	70	-0.5325	0.5961	0.7930	0.8023
S.D. RRI (SDNN)	0.0427	0.0147	70	2.9107	0.0048	0.8252	0.8023
Min RRI/task	-0.0099	0.0044	70	-2.2490	0.0277	0.8017	0.8023
Mean HR	0.0380	0.0399	70	0.9542	0.3433	0.7831	0.8023
LF HRV	0.0002	0.0001	70	1.5922	0.1159	0.8046	0.8023
HF HRV	0.0014	0.0012	70	1.1332	0.2610	0.8069	0.8023
log LF HRV	0.8949	0.4262	70	2.0999	0.0393	0.8290	0.8023
log HF HRV	0.4372	0.4144	70	1.0549	0.2951	0.8214	0.8023
log VLF HRV	0.4257	0.3125	70	1.3624	0.1774	0.8005	0.8023
LF:HF HRV ratio	0.0013	0.0005	70	2.4007	0.0190	0.7558	0.8023
Normalized HF HRV	-6.2426	3.9421	70	-1.5836	0.1178	0.7831	0.8023
Normalized LF HRV	5.9541	3.8131	70	1.5615	0.1229	0.7860	0.8023
Ventric. systole time	-0.0059	0.0117	71	-0.5001	0.6180	0.7753	0.8023
Ventric. relax. time	-0.0242	0.0228	71	-1.0610	0.2923	0.7715	0.8023
Heart muscle condt'n	0.3398	0.3834	71	0.8863	0.3785	0.7758	0.8023
Cardiac economics	-0.0537	0.1385	71	-0.3873	0.6997	0.7805	0.8023
Ventric relax % RRI	-0.2773	0.2332	71	-1.1895	0.2382	0.7811	0.8023
Systole % RRI	-0.0052	0.1709	71	-0.0303	0.9759	0.7776	0.8023
Systolic BP	0.0210	0.0263	72	0.8015	0.4255	0.8023	0.8023
Diastolic BP	-0.0363	0.0377	72	-0.9628	0.3389	0.8173	0.8023
Respiration rate	-0.1221	0.1835	70	-0.6652	0.5081	0.8023	0.8023
Min vol ventilation	0.0521	0.1027	70	0.5075	0.6134	0.8055	0.8023
Mean ETCO2/task	0.0331	0.0525	70	0.6300	0.5308	0.8110	0.8023
Min ETCO2/task	-0.1221	0.1835	70	-0.6652	0.5081	0.8023	0.8023
% sighs	0.0521	0.1027	70	0.5075	0.6134	0.8055	0.8023
MOVEMENT							
Motion sensor	8.6876	2.6121	70	3.3259	0.0014	0.7860	0.8023

Fig. 30

Percent of Variance in Task Difficulty Explained by Heart Rate and Minute Ventilation



9.2. Blood pressure

In ROC analyses with task load treated as a categorical variable with three levels, we found that blood pressure readings provided no added or significant effect for blood pressure in detecting task loads, with or without controlling for baseline (improvement in quality of detection of task load over that provided by the TLX alone

9.3. Respiratory variables

Respiratory variables did not provide additional detection of *a priori* task load over that provided by the TLX alone.

9.4. Body movement.

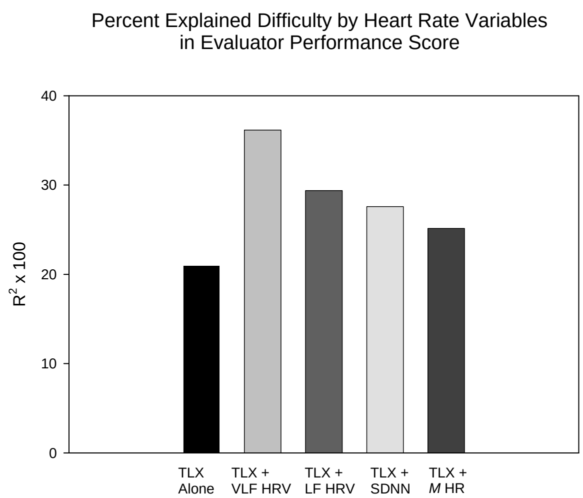
The motion detector added significant discrimination over that provided by the TLX for distinguishing High from Medium load tasks with all baseline corrections; and added significant discrimination for distinguishing High from combined Medium and Low load tasks with correction for the Breathing baseline.

10. Prediction of task performance (evaluator score) by physiological variables independently of TLX values (Table 24).

10.1. Heart rate measures

Using a multiple regression model, after controlling for total TLX values, significant added prediction was afforded by a number of cardiac variables. Including heart rate variables in the prediction equation improved the fit of the model predicting evaluator scores, as assessed by Akaike’s Information Criterion (AIC). Better performance was characterized by lower heart rate (higher RRI), lower SDNN, lower VLF HRV, and a lower LF:HF HRV ratio (as well as lower normalized LF HRV and higher normalized HF HRV, which are highly correlated with the LF:HF ratio). Including any of the heart rate in the prediction equation improved the fit of the model predicting evaluator scores over total TLX scores alone, as assessed by the AIC.

Fig. 31



10.2. Cardiac function.

Ventricular relaxation time, alone and as a function of total RRI, was negatively related to pilot performance, and heart muscle condition was positively related to pilot performance. Note that there was no relationship with either variable with *a priori* ratings of task workload. Ventricular systole time was not related to pilot performance, nor was cardiac economics. Including any of the measures of heart function in the prediction equation improved the fit of the model predicting evaluator scores over total TLX scores alone, as assessed by the AIC, although the decreases in AIC were small for systole time measures.

10.3. Blood pressure

Table 24 shows a borderline significant tendency for systolic blood pressure to be negatively related to evaluator scores. Diastolic blood pressure was not related to evaluator scores, although there was a nonsignificant trend for it to be *higher* where subjects performed well, controlling for TLX scores. Adding blood pressure to the model, however, did not improve fit of the model predicting evaluator scores, over that provided by total TLX scores, as assessed by the TLX.

10.4. Ventilation.

Lower minute volume ventilation was significantly associated with better pilot performance, but only when minute volume ventilation was controlled for values during the vanilla baseline task. There were no other significant effects for respiratory variables. Including any of the measures of ventilation in the prediction equation improved the fit of the model predicting evaluator scores over total TLX scores alone, as assessed by the AIC.

10.5. Motion.

Gross body movement, recorded from a crystal accelerometer, showed that more movement was negatively related to pilot performance, although the relationship was statistically significant only when controlled for activity in the baseline Vanilla task. Including the motion measure in the prediction equation improved the fit of the model predicting evaluator scores over total TLX scores alone, as assessed by the AIC.

Table 24a. Prediction of Evaluator Score Values by Physiological Variables, after Controlling for Total TLX Values; and Closeness of Fit of Regression Equation. All tasks, controlled for Vanilla baseline.

						AIC	
Effect	Regression Coefficient	Standard error	*df*	*T*	*p*	TLX + Physio	TLX alone
Mean RRI/task	0.0038	0.0018	97	2.0439	0.0437	323.2756	333.4667
S.D. RRI (SDNN)	-0.0143	0.0049	97	-2.9157	0.0044	320.1541	333.4667
Min RRI/task	0.0023	0.0017	97	1.3811	0.1704	327.8428	333.4667
Mean HR	-0.0531	0.0205	97	-2.5923	0.0110	320.7907	333.4667
LF HRV	-0.0001	0.0001	97	-0.6125	0.5416	326.9861	333.4667
HF HRV	0.0004	0.0005	97	0.7651	0.4461	328.9773	333.4667
Log LF HRV	-0.1290	0.1529	97	-0.8437	0.4009	326.9093	333.4667
Log HF HRV	0.2325	0.1904	97	1.2212	0.2250	327.3725	333.4667
Log VLF HRV	-0.2894	0.1052	97	-2.7498	0.0071	322.9132	333.4667
LF:HF HRV ratio	-0.0012	0.0003	97	-3.5862	0.0005	316.8618	333.4667
Normalized HF HRV	2.4835	1.2956	97	1.9169	0.0582	326.0459	333.4667
Normalized LF HRV	-2.5380	1.2637	97	-2.0085	0.0474	325.8971	333.4667
Ventric. systole time	0.0023	0.0046	98	0.4922	0.6237	331.3313	333.4667
Ventric. relax. Time	-0.0202	0.0096	98	-2.0950	0.0387	326.4939	333.4667
Heart muscle condt'n	0.3377	0.1650	98	2.0460	0.0434	325.6661	333.4667
Cardiac economics	-0.0748	0.0498	98	-1.5025	0.1362	329.7372	333.4667
Ventric relax % RRI	-0.2924	0.0871	98	-3.3588	0.0011	321.4016	333.4667
Systole % RRI	0.0006	0.0699	98	0.0089	0.9930	331.5213	333.4667
Systolic BP	-0.0186	0.0100	100	-1.8564	0.0663	333.9433	333.4667
Diastolic BP	0.0195	0.0143	100	1.3592	0.1774	332.5351	333.4667
Respiration rate	-0.0338	0.0257	80	-1.3144	0.1925	265.0734	333.4667
Min Vol Ventil	-0.0387	0.0158	80	-2.4582	0.0161	261.5349	333.4667
Mean ETCO2/task	-0.1824	0.1030	80	-1.7703	0.0805	282.5857	333.4667
Min ETCO2/task	-0.0718	0.0609	80	-1.1788	0.2420	277.4165	333.4667
% sighs	-0.0153	0.0118	80	-1.3009	0.1970	261.6709	333.4667
Motion sensor	-0.0390	0.0189	79	-2.0626	0.0424	255.3552	333.4667

Table 24b. Prediction of Evaluator Score Values by Physiological Variables, after Controlling for Total TLX Values; and Closeness of Fit of Regression Equation, all tasks, controlled for Counting baseline.

						AIC	
Effect	Regression Coefficient	Standard error	*df*	*T*	*p*	TLX + Physio	TLX alone
Mean RRI/task	0.0038	0.0018	97	2.0439	0.0437	324.0733	333.4667
S.D. RRI (SDNN)	-0.0143	0.0049	97	-2.9157	0.0044	324.5225	333.4667
Min RRI/task	0.0023	0.0017	97	1.3811	0.1704	329.2778	333.4667
Mean HR	-0.0531	0.0205	97	-2.5923	0.0110	318.6077	333.4667
LF HRV	-0.0001	0.0001	97	-0.6125	0.5416	329.3178	333.4667
HF HRV	0.0004	0.0004	97	0.7651	0.4461	329.3372	333.4667
Log LF HRV	-0.1290	0.1528	97	-0.8437	0.4009	328.4486	333.4667
Log HF HRV	0.2325	0.1904	97	1.2212	0.2250	326.4098	333.4667
Log VLF HRV	-0.2894	0.1052	97	-2.7498	0.0071	321.5840	333.4667
LF:HF HRV ratio	-0.0012	0.0003	97	-3.5862	0.0005	313.8025	333.4667
Normalized HF HRV	2.4835	1.2956	97	1.9169	0.0582	322.2374	333.4667
Normalized LF HRV	-2.5381	1.2637	97	-2.0085	0.0474	321.6413	333.4667
Ventric. systole time	0.0023	0.0046	98	0.4922	0.6237	331.5253	333.4667
Ventric. relax. Time	-0.0202	0.0096	98	-2.0950	0.0387	327.6336	333.4667
Heart muscle condt'n	0.3377	0.1650	98	2.0460	0.0434	324.3716	333.4667
Cardiac economics	-0.0749	0.0498	98	-1.5025	0.1362	329.1902	333.4667
Ventric relax % RRI	-0.2924	0.0871	98	-3.3588	0.0011	322.7112	333.4667
Systole % RRI	0.0006	0.0699	98	0.0089	0.9929	331.3632	333.4667
Systolic BP	-0.0186	0.0100	100	-1.8563	0.0663	335.1335	333.4667
Diastolic BP	0.0195	0.0143	100	1.3592	0.1771	333.7522	333.4667
Respiration rate	-0.0091	0.0258	97	-0.3538	0.7242	329.9618	333.4667
Min Vol Ventil	-0.0178	0.0240	97	-0.7387	0.4619	328.6216	333.4667
Mean ETCO2/task	0.0045	0.0726	97	0.0621	0.9506	324.5718	333.4667
Min ETCO2/task	-0.0484	0.0534	97	-0.9065	0.3669	327.1258	333.4667
% sighs	-0.0090	0.0183	97	-0.4909	0.6246	328.4731	333.4667
Motion sensor	-0.0277	0.0259	96	-1.0720	0.2865	322.3745	333.4667

Table 24c. Prediction of Evaluator Score Values by Physiological Variables, after Controlling for Total TLX Values; and Closeness of Fit of Regression Equation, all tasks, controlled for Breathing baseline.

						AIC	
Effect	Regression Coefficient	Standard error	*df*	*T*	*p*	TLX + Physio	TLX alone
Mean RRI/task	0.0040	0.0019	97	2.0675	0.0413	323.5065	333.4667
S.D. RRI (SDNN)	-0.0144	0.0053	97	-2.7318	0.0075	320.9509	333.4667
Min RRI/task	0.0015	0.0018	97	0.8252	0.4112	328.2903	333.4667
Mean HR	-0.0507	0.0203	97	-2.5050	0.0139	320.7993	333.4667
LF HRV	-0.0001	0.0001	97	-0.9608	0.3390	327.2015	333.4667
HF HRV	0.0004	0.0005	97	0.8387	0.4037	328.7966	333.4667
Log LF HRV	-0.1230	0.1771	97	-0.6942	0.4892	325.9306	333.4667
Log HF HRV	0.2917	0.1711	97	1.7042	0.0915	327.3570	333.4667
Log VLF HRV	-0.3559	0.1174	97	-3.0316	0.0031	326.3440	333.4667
LF:HF HRV ratio	-0.0013	0.0003	97	-4.1923	0.0001	316.8387	333.4667
Normalized HF HRV	3.8782	1.3038	97	2.9745	0.0037	324.9179	333.4667
Normalized LF HRV	-3.9002	1.2666	97	-3.0793	0.0027	324.6820	333.4667
Ventric. systole time	0.0019	0.0051	98	0.3629	0.7174	331.1819	333.4667
Ventric. relax. Time	-0.0195	0.0098	98	-1.9958	0.0487	329.3778	333.4667
Heart muscle condt'n	0.3885	0.1590	98	2.4427	0.0164	327.8999	333.4667
Cardiac economics	-0.0864	0.0529	98	-1.6339	0.1055	329.1294	333.4667
Ventric relax % RRI	-0.2511	0.0855	98	-2.9374	0.0041	325.1500	333.4667
Systole % RRI	0.0172	0.0706	98	0.2430	0.8084	331.5329	333.4667
Systolic BP	-0.0123	0.0105	100	-1.1612	0.2483	334.8950	333.4667
Diastolic BP	0.0202	0.0135	100	1.5022	0.1362	334.5734	333.4667
Respiration rate	-0.0146	0.0289	97	-0.5069	0.6133	323.3043	333.4667
Min Vol Ventil	-0.0277	0.0233	97	-1.1889	0.2374	328.8069	333.4667
Mean ETCO2/task	-0.0037	0.0484	97	-0.0768	0.9389	324.2436	333.4667
Min ETCO2/task	-0.0286	0.0425	97	-0.6748	0.5014	318.7550	333.4667
% sighs	-0.0014	0.0071	97	-0.2029	0.8397	330.7717	333.4667
Motion sensor	-0.0380	0.0250	96	-1.5172	0.1325	329.6873	333.4667

11. DISCUSSION AND CONCLUSIONS

This section reviews accomplishments of this research with respect to the aims of the project, as outlined above in Section 1 of this report. We emphasize, and will repeat below, that this was an exploratory study on a very small number of subjects. Thus, many borderline or nonsignificant tendencies may be found to reflect real differences in future research. Similarly, aberrant responses in a few unrepresentative subjects may account for some of the findings discussed here. The reader should keep these caveats in mind while reading the discussion and conclusions presented below.

11.1. Aims 1 and 2: Determining whether physiological measures can be reliably taken in standardized flight simulator tasks, and whether they are responsive to differences in *a* priori ratings of flight task load

In generally, we have found that physiological measures can be reliably taken in a Boeing 737B flight simulator during a variety of flight conditions, yielding interpretable results related to flight task load. Increased task load appears to be associated with decreases in heart period, and increases in sympathetic dominance, SDNN, body movement, and ventilation.

Use of psychophysiological measures to guide policy would presumably be related to ability of these measures to discriminate High from Medium load tasks. Discrimination of High from Low load task conditions would probably not require such sophisticated measurement. Although some analyses reported above only found significant discrimination between High and combined Medium and Low task loads, some, in fact, only found significant discrimination between High and Medium loads (because of lower within-group variance in this procedure), and some significant discrimination was found for both comparisons. Because of the low power of this study, we therefore conclude that further evaluation of physiological measures for discriminating High from Medium load tasks is warranted. This is important for evaluation the safety of potential new changes in flight rules. If new procedures routinely place pilots under high load, there are potential safety concerns.

11.1.1. Response of specific physiological measures to tasks of varying *a priori* task load

Heart rate and heart rate variability.

Heart rate was significantly related to work load, particularly when measured during the height of each “event” occurring during each task. Higher heart rate was related to increased load. Additionally, SDNN, as a general measure, of HRV, also was positively related to work load. In this study, the increase in SDNN appeared to be related to changes occurring in heart rate in response to particular events, rather than to endogenous sources of heart rate oscillation. Both of these measures appear to be useful as measures of workload.

Previous research has linked LF HRV to work load, with depression in LF HRV related to higher workload, except where the task is so difficult that the individual withdraws from it. In this study, although LF HRV was negatively related to self-report of task load on the TLX and, perhaps, curvilinearly related to pilot performance (evaluator scores), it was not related to *a priori* judgments of task load.

HF HRV was significantly negatively related TLX scores and positively related to evaluator scores. Higher HF HRV predicted better performance and lower self-report of workload. HF HRV is often interpreted as a reflection of parasympathetic activity, which tends to be higher in the relaxed state and be depressed during various kinds of activation. Our results are consistent with this interpretation. Our results suggest that perception of high workload and poor performance are both related to parasympathetic blockade, and that depressed HF HRV may be a useful indicator of high workload. However HF HRV was not statistically related to *a priori* judgments of task load. This is a notable example of decoupling that can occur among various indices of workload and stress. Collection of additional data may allow us to determine a cutoff for HF HRV as an index of subjective threat and performance deterioration, and whether it provides added information over the TLX for assessing the presence of high workload in a new task.

VLF HRV was inconsistently related in task load and performance. Because of the short measurement period, the VLF HRV findings probably reflected major shifts in mean heart rate during "events" in more demanding tasks, rather than heart rate oscillations reflecting changes in cardiovascular regulation or sympathetic arousal. Consistent with this was the relatively lower level of VLF HRV in the high-stress task, where task demands were constant throughout the task, compared with tasks having similarly demanding segments lasting for only part of the 5 min task duration. Although this measure may reflect workload, it overlaps other measures (e.g., maximum heart rate), and there is some difficulty in interpreting it (e.g., VLF *oscillations*, reflecting increased sympathetic tone, vs. a reflection of changes in heart rate caused by "events" in the task).

Blood pressure

Systolic blood pressure measures, taken after the tasks, significantly discriminated levels of task demand. This measure also was positively associated with self-report of workload on the TLX. Significant effects were obtained despite the fact that task events occurred at differing times during the 5-minute tasks, and blood pressure was not taken contemporaneously with the tasks, thus adding noise to the assessment of task load. We believe that systolic blood pressure holds great promise as a measure of workload, particularly if technology for on-line recording is used. No effects on diastolic blood pressure were found.

Diastolic blood pressure, on the other hand, nonsignificantly predicted better task performance, with an inconsistent but slightly negative relationship with TLX assessment of workload. In this study, diastolic blood pressure may be a reflection of task attention, involvement and coping, while systolic blood pressure appears to be related to workload. The physiological meaning of this finding requires further exploration in more subjects and with blood pressure measured contemporaneously with task performance.

Although diastolic and systolic BP often shows associated increases during stress, some differential effects have been found. Increases in diastolic blood (but not systolic) pressure are associated with greater dominance and active coping activity (Bongard et al, 1997), particularly in social situations (Davis, 1995; Newton et al, 1999), and elicitation of anger (in the emotion of anger, which focuses the individual on outward coping activity, compared with fear or sadness, which are more inhibitory and may be reflected more in systolic blood pressure responses (Pauls et al, 2003; Prkachin et al, 1999; Roberts et al, 1982; Schwartz et al, 1981). The diastolic blood pressure anger response has particularly been noted in susceptible individuals (e.g., individuals who are defensive [Pauls & Stemmler, 2003], have post traumatic stress disorder [Beckham et al, 2002] or high trait-anger [Prkachin et al, 1991; Felsten, 1996] or arousability [Mehrabian, 1995]). Increases in systolic (but not diastolic) BP is associated with social *non*dominance (Mendelson et al, 2008) and job changes (Nettersrom & Hansen, 2000), interpersonal conflict (Nealey-Morre et al; 2007), and state anxiety (Forrest & Kroth, 1971; Monk et al, 2000). Perhaps in this study the higher diastolic BP may reflect task coping and involvement, rather than a classic stress response. It is possible that examining differential systolic vs. diastolic changes in blood pressure may yield important information about workload and task performance in future research. It is possible that increases in diastolic blood pressure will yield a measure of "positive" task-involvement, whereas increases in systolic blood pressure may reflect more deleterious effects.

Ventilation.

Ventilation increased in all tasks, relative to baseline values. Some measures of ventilation also were related to higher TLX scores, including greater inspiratory time, as well as to minute volume ventilation and respiration rate. Ventilation also increased in tasks with higher *a priori* task demand.

Although $ETCO_2$ was not linearly related to TLX scores, evaluator scores, or *a priori* task load, it decreased during *all* flight tasks with respect to baseline, particularly during "events" in tasks, and during the several minutes after these events, in almost all tasks, regardless of task load. Such task-related decreases have been noted in previous literature (Ley & Yelich, 1998; Wientjes, et al, 1998). They independently can occur during anxiety and stress (Van Diest et al, 2001, 2006). This measure deserves further evaluation as an index of workload. There may be a nonlinear relationship with task performance, however. All of the lower performance scores occurred during hypocapnia periods.

Although people with normal CO_2 levels can tolerate decreases in CO_2 during exposure to stress without CO_2 levels dropping into the symptomatic range or decreasing performance, people with initially low levels may be more vulnerable to hypocapnia symptoms, as are individuals with large respiratory responses to stress and task demand. These events are not reflected in average scores, but the fact that they occur at all could have important implications for flight safety. Below we discuss more prolonged hypocapnia events that occurred during some of the flight tasks in some subjects.

Eye blinks.

Eye blink frequency also looks like a promising measure for future research, although we tested too few subjects for statistical analysis. It appears that blink frequency decreases markedly during peak task involvement, although it may increase during *anticipation* of *future* task difficulties. The decrease during peak task involvement is consistent with previous data on eyeblink activity, showing decreases during task involvement and increased work load (see paragraph 1.4.3). We did not assess differences among task in visual scanning requirements, which previous research has shown to produce decreases in blink frequency.

Body movement.

Body movement was greater during greater task load, and also correlated with TLX ratings of work load. Additionally greater body movement was related to decreases in evaluator scores of performance. Although physical activity can contribute to increased cardiorespiratory activity independently of emotional load, we have nevertheless decided not to control for it, because it is itself an aspect of workload and stress, so eliminating it would obscure our results, rather than clarify them. This measure may be a sensitive measure of workload.

Mental vs. physical demand.

In this study, mental and physical task load were highly confounded. Higher-load tasks tended to involve a higher proportion of self-reported physical load, as well as greater physical motion, as reflected in our motion detector. There is a small degree of evidence suggesting that greater sympathetic load in the LF:HF HRV measure of sympathovagal balance is associated with greater physical load, while VLF HRV (and thus perhaps HR changes during "events" in tasks) is related to greater mental load. These findings require further evaluation.

Artifact induced by some tasks

We could not take some physiological measures when the simulator itself moved suddenly, as in simulation of weather front penetration. This produced artifact in our assessment of respiratory patterns and movement, although it had little effect on measures of heart rate and HRV. We also could not take meaningful measures in tasks requiring putting on a facial mask, because donning the mask interfered with physiological monitoring sensors, and performing the task without the mask rendered it less realistic, with consequently lower levels of physiological arousal. Although our measures presumably can be taken where a mask is worn throughout a whole task, we did not test this possibility. Alternatively, a test could be done without facial sensors (thus sacrificing measures of $ETCO_2$ and blink rate).

11.1.2. Choice of flight tasks for future research

Characteristics of particular flight tasks rendered them particularly appropriate to use as "standard" tasks for assessing physiological profile of specific load levels (i.e., high load vs. medium load vs. low load), and we were able to recommend elimination of some tasks that provided duplicative data. In general, the landing tasks produced the greatest physiological flight task load differentiation, primarily because they produced higher levels of physiological response than takeoff or flight tasks.

However we also recommend including "takeoff" and "in-flight" tasks in the battery, as standards of reference for evaluation of in-flight tasks of unknown task load. We believe that elevations in some measures of physiological arousal during some lower-load takeoff tasks resulted from our having presented these tasks first. Future research should randomize the order of task presentations.

Reasons for excluding some tasks included 1) incompatibility with physiological recording procedures (as described in section 11.1.2), 2) physiological response inconsistent with load level, and 3) redundancy with other tasks.

Statistical analyses showed very small differences between analyses on all tasks that we studied and those chosen for future research. Probability values were occasionally less significant among the selected tasks because, with fewer observations on a small sample of subjects, statistical power was lower, even where the effect size was equivalent.

The recommended tasks are:

Takeoff Phase:

- T1. Normal takeoff and departure to 5000' (Baseline)
- T2. Takeoff with engine fire just after getting airborne (preset 20-30' for the fire) or just after entering the weather (100') (M)
- T3. Takeoff into a moderate to severe wind shear (H)
- T5. Lightweight takeoff with engine separation just after getting airborne (preset 20-30' for the failure) (M)

In-flight Phase:

- F1. Normal climb and acceleration from 8000' to 13000', or normal descent and deceleration from 13000' to 8000' (Baseline)

F2. Descent from 10000' with severe wake turbulence resulting in a nose-low upset starting at 8000' (disable flight freeze for entry) (H)
F5. TCAS RA (near-miss) at 10000' (M)

<u>**Approach & Landing Phase**</u>
L1. Normal visual landing from 6NM (Baseline)
L3. Manual reversion or elevator quadrant jam landing (H)
L4. Landing into a moderate to severe wind-shear (M)
L6. Landing with one main gear stuck up (H)

11.2. Aim 3: To determine whether physiological measures add detectability of task load over a commonly used self-report measure of work load [the National Aeronautics and Space Administration-Task Load Index (NASA-TLX)]

11.2.1. Self-report assessment of flight task load: relationship to *a priori* judgment of task load

As expected, NASA's TLX scale was highly correlated with *a priori* ratings of flight task load. Indeed, both are the same kind of measure: subjective measures of flight task load, one done *a priori* by experienced pilots and operators of the flight simulator facility. Some of these individuals also were subjects in this study. Therefore, the relationship between *a priori* ratings of task work load and TLX scores are not independent, and are *expected* to be very high, since some of the same people simply rated the same tasks in two different ways. Therefore, testing the significance of and added contribution of physiological measures in this experiment, over the prediction provided by the TLX, is a very conservative procedure for evaluating psychophysiology as a tool. Indeed, one would expect agreement between TLX scores and *a priori* load ratings to be nearly identical, without a chance for physiological assessment to produce an increment. This was not the case, however.

We also noted that physiological arousal (increased heart rate, decreased HRV, increased ventilation, greater movement) was related to self-perception of task load (the TLX). However, although the correlation was significant and moderately high, they were not perfect. Although it is clear that both TLX values and physiological values both reflected workload, physiological measures did not substitute for information provided by TLX values.

11.2.2. Additive detection of task load by physiological measures, over that provided by the TLX alone.

We found that adding psychophysiological measures significantly increased the prediction of *a priori* flight task load over that provided by the TLX alone. We found that combining TLX scores with heart rate, heart rate variability, ventilation, and body movement each improved prediction of *a priori* flight task load over TLX scores alone.

11.3. Additional findings: Prediction of task performance by the TLX and physiological data

As a precaution in interpreting these data, we note that our measure of task performance has not been subject to independent validation, although it is similar to ratings routinely made of pilot performance in flight simulator assessments.

11.3.1. Relationship between Evaluator Scores and *a priori* ratings of flight task load

Although evaluator scores were generally higher among less demanding than more demanding tasks, the relationship was not perfect. In tasks selected for future work we selected some high-load tasks on which subjects in this study achieved high evaluator scores mostly because subjects achieved very high scores on all tasks. Given the small number of subjects in this study, we assume that there would be some incidences of lower performance on high-load tasks in a larger subject population.

There was a moderately high correlation between *a priori* task load and pilot performance. Performance level also was negatively related to TLX assessment of flight task load: the higher the perceived task load, the worse the performance. We thus conclude that the evaluator scores did indeed assess a dimension related to task difficulty, and could be interpreted as reflecting load-related differences in performance.

11.3.2. Relationship between evaluator scores and physiological response

There was a significant linear relationship between evaluator scores and several physiological indices of arousal, including lower heart rate, lower LF HRV and possibly HF and VLF HRV. Although there was not a significant statistical relationship between evaluator scores and ventilatory data, there was evidence that very low levels of $ETCO_2$ (i.e., where hypocapnia occurred) were related to low evaluator score ratings. It is notable that hypocapnia episodes did indeed occur in this flight simulator environment, and demonstrated the negative relationship with a performance measure. Although correlational data cannot prove causality, this finding is consistent with the possibility that hypocapnia may have contributed to poor performance in some cases.

We also found that physiological measures significantly increased prediction of performance quality, over the prediction provided by the TLX alone. Thus, physiological assessment appears useful to increase sensitivity of assessing workload that is high enough to interfere with performance.

It is also notable that subjects with better cardiac function, as measured by shape of the EKG wave, tended to perform better than others, as shown in evaluator scores. Notably, shape of the EKG wave was *not* affected by task load. It thus appears that poor cardiac function may predict poorer performance.

We examined EKG measures found in Russian studies to be related to athletic performance (Bundzen et al, 1991; Dibner and Koltuk,1990). Neural control of the heart muscle is reflected in ventricular relaxation time, with greater strain on neural control related to longer ventricular relaxation time. We found that better neurocardiac control was reflected in better performance. EKG variables that reflect the economy of heart function were not closely related to pilot performance, (e.g., systole time). These variables appear important for performance under high physical load (e.g., long distance running). These conditions did not appear relevant to performance in the cockpit in our study.

Further evaluation of these variables in a younger population representative of line pilots must be undertaken before these findings are used for formulating policy. It also is possible that these cardiac variables may be used as a guide for pilots in their own physical fitness programs, to help them know when they are achieving levels of fitness that might improve performance.

11.3.3. Parabolic function and cut-offs in relationship between physiology and performance

We also note some evidence for a curvilinear relationship between physiological arousal and task performance. Some of our data are consistent with prediction of the Yerkes-Dodson law (Yerkes &

Dodson, 1908),[1] showing peak performance levels under levels of moderate physiological arousal. This appeared to be the case for heart rate and for LF HRV. We note, however, that with our small sample of subjects and low variability in performance (with pilots receiving the highest score on the great majority of tasks), conclusions about the relationship between task performance and physiological arousal remain highly tentative.

11.3.4. Added predictability of pilot performance from physiological measures over TLX scores alone

Significant added linear predictability of performance was provided from two measures of sympathetic: parasympathetic balance (the LF:HF HRV ratio) and VLF HRV. Although interpretation of VLF HRV is clouded by the brief assessment period in each task, these results suggest that higher sympathetic arousal predicted poorer performance. It is possible, however, that the VLF measure reflected task-related shifts in level rather than a change in actual HRV oscillations in this frequency range. Traditional interpretations of VLF HRV cannot be made in the relatively brief task periods in this study, with nonstationary conditions. However, it is notable that heart rate and overall HRV also provided added predictability (over the TLX alone) for predicting task performance. If VLF HRV is interpreted as reflecting shifts in baseline heart rate during “events” in the tasks, it appears that better performance is related to smaller shifts in HR: i.e. that a larger heart rate increase during the events was related to poorer performance.

The amount of additive prediction of evaluator score values was increased when values were controlled for baseline values, using difference scores. Additionally adding baseline values to the model had little effect, indicating that the size of the change from baseline (i.e., difference score) and its predictive value for evaluator scores were not dependent on the actual baseline value. Also, it appeared to make little difference which of the three baseline conditions we controlled for: baseline vanilla task, counting task, or 6/min breathing task. Thus, it appeared that, although effects were related to baseline levels, they were not specifically related either to specific physiological reactivity to nonflight cognitive load or to brainstem level autonomic reactivity to stimulation. Future research might therefore fruitfully use just a simple nonload task, such as the vanilla baseline task. We therefore conclude that taking a nonflight baseline task is important for future studies of flight-task-related workload.

11.4. Aim 4: Determining whether potentially unsafe levels of physiological arousal may occasionally occur in any individual subject during high-load flight maneuvers in the flight simulator situation.

In deciding whether a potential flight rule is safe for routine application, presumably it should not elicit unsafe physiological reactions at any time, even if they occur only rarely. In evaluating new flight rules, it would be important to identify those that might elicit potentially catastrophic effects of deteriorated performance due to hyperventilation or cardiovascular failure. Our study showed that such extreme reactions can be elicited in the flight simulator, and that this form of task evaluation could be a valid method for evaluating flight task load.

11.4.1. Hypertensive reactions*.*

[1] Note that, although the Yerkes-Dodson inverted ‘U’ function between physiological arousal and performance has been widely used and replicated, the exact formulation of the Yerkes Dodson law has been criticized as vague and inexact (e.g., Teigen, 1994). It is used here for heuristic purposes.

Three of the seven pilots showed elevations in blood pressure in at least one task that is conventionally considered to increase risk of stroke. There is at least circumstantial evidence that stroke has been involved in several fatal airplane disasters. Hypertensive reactions would be a particular risk among individuals with untreated high blood pressure, as may have been the case in one of our subjects. Presumably such individuals would not be flying, although one report suggests that even and individual with *treated* hypertension may be at risk for a disabling stroke while piloting an aircraft (NTSB Identification: SEA03FA045, March 15, 2003). However, our results show that a high-demand task may produce prolonged changes in blood pressure among susceptible individuals, and that these can be at levels that could be of possible medical significance.

11.4.2. Hypocapnia episodes.

When increased ventilation is accompanied by increased metabolic rate, and the two are perfectly matched, blood levels of pCO_2 usually do not change. However when ventilation exceeds metabolic need, pCO_2 decreases, sometimes leading to hypocapnia. Such "mismatch" is common, and is exaggerated under conditions of high workload (Dempsey et al, 1988, 2006) and when the individual's adaptive capacity is compromised by physical or emotional disease (Ponikowski et al, 2001; Prabhakar & Peng, 2004; Rossiter et al, 2003; Whipp, 1983), and often occurs during shifts in metabolic need, where ventilation usually overcompensates for changes in metabolic need. When baseline levels of pCO_2 are close to hyperventilatory levels, actual hypocapnia can then occur.

Surprisingly, we found that task involvement during "events" occurring in each tasks produced brief periods of hypocapnia in almost all subjects. In most cases this involved only one or two breaths, an insufficient time to produce significant effects on brain blood flow or performance. However, as described below, more prolonged hypocapnia episodes also occurred, showing that the flight simulator situation is capable of producing hypocapnia, despite lack of several respiratory stimulants commonly occurring in the cockpit in actual flight (decreased air pressure, increased ambient CO_2, very low humidity, and air pollution. Thus, incidence of hypocapnia found in this study is probably an *underestimate* of its occurrence in actual flight conditions.

Two of three subjects on whom we measured $ETCO_2$ showed evidence of clinically significant hypocapnia for 15 minutes in at least one of the tasks. Although this period of hypocapnia time could have affected brain function and judgment, the level of hypocapnia was only on the borderline of the level expected to produce decrements in performance on visuomotor tasks, which occurs at levels below 25 mm Hg (Gibson, 1978; Van Diest et al, 2000). Decreased performance on cognitive tests has been documented at pCO_2 levels < ~32 mm Hg. (Marangoni & Hurford, 1990; Rahn et al, 1946). There is almost a linear decrement in flicker sensitivity with pCO_2 from 40 – 20 mm Hg. in voluntary hypocapnia (Connolly & Hosking, 2007). Flicker sensitivity correlates highly with alertness, and is often used to measure alertness in various drug trials (Schneider et al, 2004). The level of hypocapnia that impairs pilot performance appears to be at approximately the same level (Balke & Lillehei, 1956). We found a borderline significant negative relationship between evaluator score and $ETCO_2$ controlled for TLX scores, and a significant negative relationship with increased ventilation. The relationship between hyperventilatory episodes and pilot performance warrants further research, and our data show that this relationship can be examined in the flight simulator.

As noted in the Introduction, hypocapnia can be a risk in aviation. In addition to flight task load and stress, other respiratory stimulants may also occur in the cockpit environment, including decreased air pressure, cabin pollution, and elevated ambient levels of CO_2. Detecting and avoiding tasks that could potentially trigger prolonged hyperventilatory episodes may, therefore, by highly useful for assuring safety.

11.5. Aim 5: Assessing a psychological trait that is often related to underreport of subjective stress and to exaggerated physiological response, and to determine whether these relationships are present among pilots tested in a flight simulator.

A few cases, as presented above, are consistent with previous findings showing that the psychological trait of defensiveness, as assessed by the MCSDS, is associated with both diminished self-report of stress, as expressed in this study as workload ratings on the TLX, and with elevated psychophysiological reactivity. However, including this measure in the statistical model does not lead to improvement in prediction of evaluator scores, either by the TLX or physiological assessment. Although future research may find a role for this instrument in future psychophysiological aviation research, our current results do not indicate that the instrument must be used regularly in this research.

Nevertheless, the trait of defensiveness may be more common among pilots than in the general population. All subjects in the current study scored higher than the averages usually found in studies using this instrument. The trait involves a reluctance to disclose negative things about oneself, including uncomfortable body sensations and emotional reactivity. The aviation culture does not encourage such self-disclosure. Indeed, people who score high on this instrument tend not even to *perceive* certain negative sensations. For example, they tend to have lower pain thresholds than others, although their elevated physiological responsiveness may put them at greater cardiovascular risk. This may, indeed, be an adaptive trait among pilots: it may promote cool and methodical behavior under conditions of stress, with less emotional interference in relating to crew, air traffic controllers, and task performance, and an ability to ignore pain and discomfort, in the interest of maintaining the highest level of task performance.

Defensive individuals tend to show lower levels of self-reported stress, anger, or anxiety, but *highe*r levels of heart rate and blood pressure levels and reactivity (Asendorpf & Scherer, 1983; Jamner et al, 1988; Miller, 1993; Shapiro et al, 1993, 1995, 1996; Weinberger et al, 1979), electrodermal activity (Benjamins et al, 1994; Tomaka et al, 1992; Weinberger et al, 1979), and muscle tension (Weinberger et al, 1979). Defensiveness also has been associated with elevated salivary cortisol (Brown et al, 1996) and cholesterol levels (Niaura et al, 1992) and lower respiratory sinus arrhythmia (Broomfield et al, 2005; Fuller, 1992; Pauls et al, 2003; Movius et al, 2005). Autonomic effects, such as chronic sympathetic arousal, may directly contribute to the onset or exacerbation of disease among defensive individuals. Defensive individuals also show higher blood lipid levels (Barger et al, 2000; Niaura et al, 1992) and blood pressure (Shapiro et al, 1996, 1997) and more evidence of cardiovascular disease (Jorgenson et al, 2001). They show higher levels of cortisol, a steroid associated with stress Brody et al, 2000). Studies from our laboratory found that defensive individuals with asthma tend to show exaggerated stress-related bronchoconstriction (Feldman et al, 2002) but also tend to *report* fewer respiratory sensations when exposed to an external respiratory resistive load (Isenberg et al, 1997). Dissociation between physiological and self-report indices of anxiety or stress is magnified among people who score high on defensiveness (usually the MCSDS) (Contrada et al, 1997a,b; Newton & Contrada, 1992; Shapiro et al, 1995). Given the systematic association between defensiveness and high sympathetic/low parasympathetic activity and simultaneous association with low self-report of anxiety or stress, the dissociation between autonomic and self-report measures would be expected to decrease when measures of repressive coping are factored in.

Although only relatively extreme defensiveness scores tend to be associated with the pattern of minimization of self-report stress symptoms and exaggeration of physiological response, the results in this small sample suggests that this level may be common among pilots, and that it may predict which pilots will show the greatest underreport of work-load in flight simulator tasks, at least in some individuals, despite the lack of an overall statistical trend. Further evaluation of this variable in a larger population is warranted, despite lack of statistically significant findings in this small study.

11.6. Caveats

This study was designed as a preliminary investigation, in order to develop a psychophysiological assessment methodology, rather than to offer conclusive findings. We therefore performed multiple statistical tests, in order to detect the best tasks and measures for use in future research. However, because of the large number of comparisons made, the exact probability values are not definitive. Some of our statistical findings may have resulted from response peculiarities of particular subjects, and may not be replicable.

Also, most importantly, this study was done on very few subjects. Thus, the low power of the study's statistical design was very low. The small number of subjects did not permit calculation of a meaningful physiological index, or development of norms for physiological measures. Also, statistical trends found in a small population require validation in a larger sample, because idiosyncratic responses in a small number of subjects might have unduly influenced overall results. Indeed, we know that some of our subjects were unrepresentative of the general population of airline pilots. The following characteristics differentiate them from the general population of pilots:

1. Most of our subjects were older than the average pilot
2. Some of our subjects would not have met health requirements of the FAA
3. Some of the subjects were involved in creating the *a priori* task load ratings, so the relationship between TLX scores and task loads were likely inflated
4. A more standardized method of pilot performance assessment needs to be developed and validated. The method used in this study was *ad hoc.*

Finally, we note that some of the subjects in this study were involved in *a priori* categorization of task loads, so the TLX and task load designations were not independent. Thus the relationship between TLX values and *a priori* ratings of task load may have been exaggerated in our study, and thus the added contribution of physiological measures, over the TLX, to detecting task load may have been systematically underestimated.

11.7. Implications for management of work load

The primary goal of this research was to aid in development of more sensitive methods for detecting high work load conditions in various flight procedures. Methods developed in this project could be put to other uses as well.

1. *Assessment of training adequacy.* It is possible that a "high demand" task may, after training, show a reduction in the load it places on the pilot. Psychophysiological assessment may be useful in monitoring such an effect.
2. *Development of psychophysiologically-based interventions to lessen ill effects of high work load.* If psychophysiological changes are indeed related to pilot performance, then pilots could be trained both to recognize symptoms of these changes, and to control their effects. Two developments in applied psychophysiology might be relevant here:
   a. *Slow breathing.* Research by Bernardi and his colleagues has found that breathing slowly, at about 6 breaths/minute, minimizes the tendency to hyperventilate. They found that people trained in Yoga breathe at about this rate and people who breathe at

this rate while reciting a rosary prayer or are simply instructed to breathe at this rate show resistance to hypocapnia in a hypoxic ventilatory challenge (Bernardi et al, 2001a,b). People dwelling at high altitudes learn to breathe slowly to avoid some of the effects of altitude-induced hypocapnia (Keyl et al, 2001). Research from our laboratory has found that there is a particular respiration rate for each person, at about 6 breaths/minute, at which heart rate and respiration are fully in phase with each other (Vaschillo et al, 2006). When people are specifically taught to breathe at this frequency they show stronger baroreflex gain and more efficient respiration (Giardino et al.; Lehrer et al, 2003), which also was true in Bernardi's studies. This, in turn, may mediate a tendency for this training to improve symptoms of respiratory disease (Lehrer et al, 2004; Giardino et al, 2004), and to modulate effects of stress and anxiety (Thurber, 2007). It also may inoculate the individual against hypocapnia.

b. *Neural network control.* A recent study by Wilson and Russell (2007) employed a neural-network-based system of multichannel biofeedback to aid subjects in modulating and pacing their own work load to achieve optimum performance in an uninhabited aerial vehicle task. Such multichannel assessment of work load is similar to that being developed in this research. They found improved performance accuracy with this system of feedback.

11.8. Conclusions

1. Psychophysiological data add significant information over the conventionally used TLX scale in assessing flight task difficulty. They add information for discriminating high-load tasks from tasks with lesser load.
   a. Our data need to be replicated in a larger sample in order to confirm this finding.
   b. Additional data are needed in order to determine norms and cut-off scores for physiological data
   c. Although we did not have sufficient data to calculate a physiological index, it appears likely that the following measures would comprise such an index, with other measures (particularly HF HRV and $ETCO_2$) perhaps adding information in a larger-scale study:
      i. RRI during maximum-load events in each task (which easily can be calculated as the minimum RRI during the task)
      ii. Respiration rate
      iii. Minute volume ventilation
      iv. Body movement
   d. Further information is needed about eyeblink activity to determine whether it should be included in a physiological index
   e. Baseline tasks are useful in rendering physiological data more sensitive to flight task load.

2. We have chosen a smaller number of flight tasks that can be used for developing norms relating to flight task load

3. Individuals who score high on defensiveness (using the Marlowe-Crowne Social Desirability Scale) may show lower scores on the TLX and higher psychophysiological task reactivity than others. This scale should be used in further research.

4. Some pilots may experience extreme levels of physiological arousal in high-load tasks in a flight simulator. Tasks of unknown load which elicit such responses should be considered as having high load, and may represent a physiological flight safety risk. Further research is necessary in order to determine the extent of this risk.

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