The moderating role of end-tidal CO₂ on upper trapezius muscle activity in response to sustained attention.

With higher levels of automation in modern manufacturing, there is increased monitoring of the process by the human operator. Prolonged monitoring or sustained attention has been found to be stressful for human operators. Plant and process operators have also been found to have one of the highest level of work demands (work speed, pace) in a recent European survey (Eurofound 2015). Along with this, the incidence of Work Related Musculoskeletal Disorders (WRMSDs) remains at a high level in the manufacturing sector. This research endeavoured to determine if end-tidal CO₂ levels decreased and upper trapezius muscle activity increased concurrently with increased levels of attention. We then developed a model to investigate if end-tidal CO₂ moderated the relationship between mental workload due to sustained attention and upper trapezius muscle activity. The resulting interactional model found that end-tidal CO₂ moderated the relationship (p=0.004) when end-tidal CO₂ reached the hypocapnic range (>35 mm Hg). This model indicates the possibility that a high level of sustained attention is a risk factor in the development of WRMSDs and should therefore be included in workplace risk assessments.

Keywords: Sustained attention, mental workload, muscle activity, work related musculoskeletal disorders

1.0 Introduction

The globalisation of financial and product markets are increasing international competition, resulting in rapid technological change and expectations for higher performance at both the corporate and individual levels (Narula 2014). This has contributed to an emerging trend of work intensification with an increase in workload and work pressure (European Agency for Health and Safety at Work 2007, Eurofound 2015). Industry is meeting this challenge through increasing levels of automation and robotics technology (Probst et al. 2013). Between 2015 and 2018, it is estimated that about 1.3 million new industrial robots will be installed in factories around the world (IFR 2015). One motivator for advancements in automation technology has been the reduction in human mental workload, albeit that increased monitoring creates mental workload in itself (Lee 2006, Parasuraman et al. 2000). Increased cognitive demand for operators acting as system supervisors is likely to arise from the requirement for additional monitoring of automation (Kaber and Endsley 2004, Warm et al. 1996). Sustained attention is a dominant component of job content in modern
manufacturing and it is likely that the duration of monitoring required has increased in line with work intensification. Hancock (2013) ascertains that while sustained attention has always been part of human life, operators’ lack of control of the focus of their attention within modern automated environments is a source of stress.

1.1 Sustained attention

Sustained attention or vigilance refers to the ability to maintain focus of attention and to remain alert to stimuli over prolonged periods of time (Molloy and Parasuraman 1996). There are two main theoretical approaches which explain vigilance. The mindlessness model is based on the premise that repetitive and monotonous tasks reduce the level of stimulation required by the central nervous system resulting in a lowered sensitivity to signal detection (Heilman 1995, Manly et al. 1999, Robertson et al. 1997, Thomson et al. 2015). It is proposed that as the mind disengages from the task, it is preoccupied with task unrelated thoughts (Giambra 1995, Smallwood et al. 2004, Allen et al. 2013). The attentional resource theory is an alternate view has also been used to understand the concept of vigilance (Fisk and Scerbo 1987, Fisk and Schneider 1981, Wickens 1984, Warm et al. 2015). Contrary to viewing attention tasks as under stimulating, this approach considers vigilance as being resource demanding and posing significant mental workload for operators. Experiments using two subjective mental workload scales, the NASA Task Load Index (NASATLX) (Hart and Staveland 1988) and the Multiple Resources Questionnaire (Boles and Adair 2001, Boles and Dillard 2015), have demonstrated that vigilance tasks are highly mentally demanding where there are multiple sources of workload (Finomore et al. 2008, Finomore et al. 2009, Finomore et al. 2013, Warm et al. 1996). Recent neuroimaging studies have shown that sustained attention is a stressful task for human beings (Warm et al. 2008). It has also been reported that stress hormones or catecholamine levels are elevated during sustained attention tasks (Frankenhaeuser 1976, Lundberg and Frankenhaeuser 1980, Lundberg 2005). Matthews et al. (1999) using the Dundee State Stress Questionnaire (DSSQ) showed that vigilance tasks lead to a loss of task engagement and an increase in feelings of distress, and that these changes increase as task difficulty increases. We can therefore surmise that humans are poor at vigilance tasks (Hancock et al. 1995). These tasks impose significant mental workload on human operators and can be stressful (Warm et al. 2008).

1.2 Links between mental demand and musculoskeletal disorders
Excessive mental demand due to prolonged monitoring by manufacturing operators is likely to contribute to adverse health effects. Along with evidence that mental demand due to sustained attention is stressful for humans, it has also been linked to an increase in muscular activity. Consequently, high mental demands have been found to increase the risk of work related upper limb disorders (WRMSDs), (Smith et al. 2004, Elovainio and Sinervo 1997, Sjøgaard et al. 2000, Laursen et al. 2002). WRMSDs refer to a broad range of inflammatory and degenerative conditions that affect the body’s muscles, tendons, ligaments, joints and blood vessels (Punnett and Wegman 2004). Across the 27 EU Member States, WRMSDs represent the most common work related health disorders. WRMSDs represented 38% of all recognized diseases covered by the European Occupational Diseases Statistics in 2005 (EUOHSA 2010). The burden posed by musculoskeletal disorders is predicted to increase particularly in developing countries (Woolf et al. 2012).

Researchers have suggested a variety of mechanisms underlying the relationship between computer work and musculoskeletal problems (Sauter and Swanson 1996, Bongers et al. 1993, Smith and Carayon 1996, Lim 1994). Hagg (1991) proposed that low levels of muscle tension can contribute to WRMSDs of the upper extremities, neck, and shoulders. Sustained static postures, where operators maintain prolonged attention on a computer screen may contribute to low level static muscular loading by keeping muscles tensed over long periods particularly in the neck and shoulder regions of the upper body (Waersted and Westgaard 1996). If the muscle has little opportunity to relax from a sustained posture during the working day, muscular fatigue can occur even at low levels of physical activity, leading eventually to muscular injury (Enoka and Stuart 1992, Jonsson 1988). Static muscular loading also leads to a deficiency in blood circulation (Sjøgaard et al. 1988) and the reduced blood flow increases the concentration of metabolites and inflammatory substances in the muscle resulting in additional sensitivity and pain (Rosendal et al. 2004). Knardahl (2002) postulates that vasodilatation of skeletal muscle during cognitive tasks like monitoring work originates from nociceptive interactions in the connective blood vessels that supply the muscle.

**1.3 Hyperventilation**

A further theory linking stress to muscle activity is the hyperventilation theory. This theory posits that job stress can be linked to WRMSDs through a breathing mechanism called hyperventilation (Schleifer et al. 2002). Hyperventilation refers to breathing that exceeds the metabolic requirements for oxygen (West 2012, Gravenstein et al. 1995). It can be measured
by detecting a decrease in end-tidal CO$_2$, (partial pressure CO$_2$) at the end of an exhaled breath (LaValle and Perry 1995). Hyperventilation causes a drop in arterial CO$_2$ resulting in hypocapnia and respiratory alkalosis. This disruption in acid-base equilibrium will in turn trigger a neuronal excitation causing increased muscle tension and spasms with adverse effects for muscle tissue.

It is known that respiration is sensitive to cognitive workload. Under conditions of stress, the respiration rate increases and the mode of respiration shifts from diaphragmatic or abdominal breathing, to thoracic or chest breathing, and hyperventilation occurs (Naifeh 1994). The literature to date has shown evidence for a relationship between mental stress and end-tidal CO$_2$. Greater reductions in end-tidal CO$_2$ were found in students who were anxious above those that weren’t during a memory test (Ley and Yelich 1998). End-tidal CO$_2$ was found to successfully differentiate between three cognitive test conditions when respiration rate and interbeat interval could not (Schleifer and Ley 1994b). A further study by Schleifer et al. (2008) proposed that lowered end-tidal CO$_2$ may mediate trapezius muscle activity during computer data entry tasks. While it has been shown that those in a state of hypocapnia (reduced CO$_2$ in blood) resulting from hyperventilation have reduced attention (Van Diest et al. 2000, Matthews et al. 2010), limited information is available on the situation where end-tidal CO$_2$ changes due to sustained attention. In spite of findings that end-tidal CO$_2$ is a sensitive differentiator of cognitive tasks, it has not been widely studied in the area of mental workload or in terms of its relationship with muscle activity.

### 1.4 Upper Trapezius Muscle Activity

Upper trapezius muscle activity has been found to be indicative of upper body muscular activity in general (Visser and van Dieën 2006), and has been shown to increase activity via psychosocial stress mechanisms (Wijsman et al. 2013). Upper trapezius muscle activity was therefore selected for this study. In relation to computer work in particular, increases in shoulder muscle activity have been linked to mental demands (Wijsman et al. 2013, Sjøgaard et al. 2000). Trapezius muscle activity has also been found to be a good indicator of emotional stress (Cacioppo and Tassinary 1990). Waersted and Westgaard (1996), in their study of task-irrelevant attention, found that upper trapezius muscles were sensitive to changes in attention. A recent study which focused on young workers found that prolonged increases in trapezius muscular activity was linked to the development of neck and shoulder pain (Hanvold et al. 2013). A further explanation for the influence of psychosocial stress
factors on upper extremity musculoskeletal disorders is that hyperventilation imposes a biomechanical load on the neck/shoulder region. This is a direct result of the shift from abdominal to chest breathing, as upper trapezius muscles are more active during chest breathing (Criswell 2010).

1.5 Research Rationale
This study is based on the hyperventilation theory of job stress and musculoskeletal disorders (Schleifer et al. 2002), and attempts to fill a gap in the literature in relation to the relationship between sustained attention, end-tidal CO₂ and upper trapezius muscular activity. We evaluated sustained attention as a risk factor in the development of WRMSD complaints. End-tidal CO₂ has been proposed as a mediator in the relationship between mental workload and upper trapezius muscle activity (Schleifer et al. 2008). This study however, investigated whether end-tidal CO₂ is a moderator of this relationship at concentrations of end-tidal CO₂ in the hypocapnic range (<35 mmHg). A mediating variable is one that creates an indirect relationship between two variables. In other words, a mediator is necessary to be present in order for the relationship to occur. A moderator variable is a variable that affects the strength of the relationship between two variables (Hayes 2013) and is characterised as a significant interaction. Moderating variables indicate when and under what conditions an effect can be expected.

We hypothesize that (a) end-tidal CO₂ levels decrease in line with increased levels of sustained attention; and (b) that end-tidal CO₂ is a moderator in the relationship between sustained attention related-mental workload and upper trapezius muscle activity.

2.0 Method
2.1 Study Design
The dependent variable was upper trapezius muscle activity, the independent variable was sustained attention related mental workload and the moderating variable was end-tidal CO₂.

2.1.1 Upper Trapezius Muscle Activity. Surface EMG was recorded using disposable, pre-gelled dual Ag/AgCl electrodes (Covidien H124SG 24 mm). A Nexus 10 (Mind Media BV)
physiological monitoring and feedback platform with Bluetooth communication was used for recording muscle activity at a sampling rate of 2048 Hz. Raw Root Mean Square (RMS) values were averaged over 1/8 second epochs using the Biotrace software programme. The bandpass DC corrections were set at 0.1 Hz. A digital 4th order Butterworth cascaded IIR bandpass filter was set to 20-500Hz in the Biotrace software. Impedence of the active channels was set at $10^{12} \Omega$.

2.1.2. Mental Workload

Each participant underwent four study conditions that required different levels of mental workload. These were the baseline or rest condition and three separate attention tasks: NBACK, SART and AVT which required low, medium and high levels of attention respectively. The baseline condition required participants to sit at a computer workstation in front of a blank computer screen for 12 minutes. Three levels of attention tasks were included to reflect variation in the degree of attention required in industry. The level of mental workload was measured for each task using the NASA task load index.

Attention Tasks. The N-back test (Jaeggi et al. 2008) was the low attention test. It involved a square appearing every 4.5 seconds in one of eight different positions on a white grid placed on a black computer screen. The participant had to respond by pressing the ‘Y’ key on the keyboard if the position of the displayed square was the same as the one that was presented immediately prior.

Two tests requiring high levels of sustained attention, the Sustained Attention to Response Test (SART) (Robertson et al. 1997) and the Abbreviated Vigilance Test (AVT) were also used. The SART has been widely used to test sustained attention (Smallwood et al. 2004, Cheyne et al. 2009). In this method, 675 single digits (75 of each of the nine digits) were presented visually over a 12.9 min period. Each digit was presented for 250 msec, followed by a 900 msec mask. Participants responded with a key press of their dominant hand to each digit, except for 75 occasions on which the digit 3 appeared, when they had to withhold a response. Both digits and mask were presented centrally on white, against a black computer screen.

The abbreviated vigilance test is a 12 minute test divided into six periods of 2 minutes. The numerals O, D and a backwards D are presented in a repetitive format as 8 X 6mm light grey capital letters. The letters (24 point in Avante Garde font) were shown for 40 ms against a
visual mask consisting of unfilled circles on a white background. Stimuli were presented at a rate of 57.5 events/minute which is considered to be a very high event rate (Nuechterlein et al. 1983). The critical signal for detection was ‘O’. The order of presentation of the three stimuli was randomised and detection of the critical signal was recorded by participants hitting the space bar with their dominant hand. This test has reproduced the high workload and the stressful character of vigilance tasks lasting 30 minutes or more (Temple et al. 2000).

2.1.3 NASA—Task Load Index. The NASA-task load index (NASA-TLX) is a well-regarded instrument used to measure the level of perceived mental workload experienced during tasks (Hart and Staveland 1988, Nygren 1991, Proctor and Van Zandt 1994, Wickens et al. 2015). This scale identifies the relative contributions of six sources of workload: mental demand, temporal demand, physical demand, performance, effort, and frustration. Previous research has shown that vigilance tasks are mentally demanding with mental demand and frustration being the principal components of the NASA-TLX associated with vigilance tasks (Szalma et al. 2004, Helton et al. 2005, Warm et al. 2008). The NASA-TLX scale was presented in hard copy format.

Scoring was on a Likert scale from 1 to 7, with 1 representing no effort and 7 representing maximum effort. Indices of validity, reliability and discriminating power have been shown to improve when response scales had up to a 7 response option, and the test-retest reliability decreased with response scales greater than 10 (Preston and Colman 2000), therefore a 7 point scale was chosen in this study. The NASA-TLX paired comparison procedure was not included in the study as is not deemed critical for valid workload assessment (Nygren 1991). The unweighted score were used for the analysis (Hendy et al. 1993). The final score was reported out of 100 to make it comparable to other studies.

2.1.4. End-tidal CO2.

End-tidal CO2 is hypothesised as a moderator variable in this study. In this context, end-tidal CO2 is a third variable that represents the conditions under which the effect of attention related mental workload on upper trapezius muscle activity (dependent variable) become maximally effective. Peak concentrations of carbon dioxide gas in expired air were measured using the CosMED K4B2 physiological measurement system. This system is a sidestream capnograph where the exhaled CO2 is aspirated via a mask through a sampling tube connected to the instrument for analysis. Samples were taken every 5 seconds and averaged over each task. The partial pressure of end-tidal CO2 is highly correlated with alveolar pCO2.
The normal values are 5% to 6% CO$_2$, which is equivalent to 35-45 mmHg (Hollinger and Hoyt 1995).

### 2.2 Participants

Twenty two participants, 12 male and 10 female undergraduate students ranging in age from 18 to 41 (M= 21.21, SD=5.35) provided written informed consent to take part in the experimental study. Local ethics approval was granted prior to participant recruitment.

### 2.3 Procedure

Each participant was informed of the purpose of the experiment. Participants completed a health history questionnaire and met the following criteria (a) did not suffer from musculoskeletal disorders (b) had no history of cardiovascular disease and (c) were non-smokers. All participants had normal or corrected to normal vision. The Edinburgh handedness inventory (Oldfield 1971) was also completed by all participants. Twenty one of the twenty-two participants were right-handed. The physiological measurement equipment was then attached to each participant.

#### 2.3.1 Upper Trapezius Electromyography

Surface EMG was recorded from the non-dominant upper trapezius muscle by placing the Ag/AgCl electrodes centred on a point 2 cm lateral to the midpoint between the acromion process and the spinous process of the seventh cervical vertebrae. A bipolar configuration was employed with a centre to centre interelectrode distance of 20 mm. Active electrodes were referenced to a ground electrode placed over the radius bone on the participants non-dominant inner wrist. Electrode placement and skin preparation was performed in line with the SENIAM protocol (Stegeman and Hermens 2007).

#### 2.3.2 End-tidal CO$_2$

End-tidal CO$_2$ (PetCo$_2$ mmHg) concentrations in expired air were measured by attaching a fitted facemask to each participant. A fit–test was performed by asking each participant to place their hand over the inlet of the face mask while breathing out to detect any leaks.
2.4 Test Conditions

Participants completed four test conditions, baseline, NBACK, SART and AVT. The baseline condition was completed first for each person. Participants were asked to sit at the workstation in a neutral posture, their shoulders relaxed, the left forearm and hand (non-dominant hand) resting on the computer workstation. The users’ right arm was placed so that the elbow was flexed 90°, their forearm was resting on the workstation surface and their hand positioned on the computer keyboard. For each test the screen was positioned approximately 40 cm from the participants’ eyes. Latin square orders (Dénes and Keedwell 1974) were used to vary the sequence of tasks for each participant. Each condition was approximately 12 minutes in length. Rest periods, where the participants were asked to relax between each test were 12 minutes long. Each participant completed a NASA-TLX questionnaire at the end of each attention task.

2.5 Statistical Analysis

Statistical analysis was carried out using the SPSS 22.0 software package. End-tidal CO₂ and NASA-TLX mental workload data were normally distributed. The surface electromyography (raw RMS) data were non-normally distributed and underwent log normal transformation to a normal distribution. Statistical testing was then carried out using repeated measures ANOVA tests with significance levels set at the 5% level. Post-hoc analysis was performed using the Bonferroni correction. The assumption of sphericity (Mauchly’s test) was violated for end-tidal CO₂ and upper trapezius muscle activity so Wilks lambda was therefore reported for these variables (Pallant 2013).

Moderation analysis was then carried out using the PROCESS macros (SPSS 22.0), which generates a multiple linear regression based path analysis resulting in a moderation model (Hayes 2013). The data were mean centred in order to plot the simple slopes and Johnson-Neyman graphs. In constructing the simple slopes plots, the SPSS programme automatically divided the mental workload scores and the PetCO₂ results into three levels for each variable: low, average and high. Simple slopes show changes in the dependent variable at varying levels of the independent and moderating variables. The Johnson-Neyman plot shows the point of significance (p=0.05) at which the effect of mental workload on end-tidal CO₂ starts to cause an increase in upper trapezius muscle activity.
## 3.0 Results

Table 1 gives a summary of descriptive statistics of upper trapezius muscle activity and end-tidal CO2 data for all study conditions. It also gives the significance levels, F-values and η² for repeated measures ANOVA on the effect of the task (baseline, NBACK, SART and AVT) on upper trapezius muscle activity and end-tidal CO₂.

### Table 1: Descriptive statistics and ANOVA of physiological variables for baseline and attention tasks

<table>
<thead>
<tr>
<th></th>
<th>BASELINE</th>
<th>NBACK</th>
<th>SART</th>
<th>AVT</th>
<th>ANOVA*</th>
<th>F-value (df1, df2)</th>
<th>η²</th>
<th>Sphericity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (S.E.)</td>
<td>Mean (S.E.)</td>
<td>Mean (S.E.)</td>
<td>Mean (S.E.)</td>
<td>Mean (S.E.)</td>
<td>Mean (S.E.)</td>
<td>Mean (S.E.)</td>
<td>95% CI</td>
</tr>
<tr>
<td>Upper Trapezius Activity (µV)</td>
<td>6.52 (1.08)</td>
<td>4.29 (2.57)</td>
<td>18.23 (3.43)</td>
<td>12.91 (2.07)</td>
<td>24.76 (3.43)</td>
<td>17.64 (2.07)</td>
<td>22.22 (3.43)</td>
<td>17.94 (3.43)</td>
</tr>
<tr>
<td>End-tidal CO₂ (mmHg)</td>
<td>34.01 (0.81)</td>
<td>32.33 (0.69)</td>
<td>33.92 (0.63)</td>
<td>32.48 (0.63)</td>
<td>32.73 (0.63)</td>
<td>31.42 (0.63)</td>
<td>33.19 (0.63)</td>
<td>31.90 (0.63)</td>
</tr>
</tbody>
</table>

1A one-way repeated measures ANOVA. *The mean differences are significant at the 0.05% level. L. denotes lower and U. upper confidence intervals.
3.1 NASA-TLX for the task conditions

One-way repeated measures ANOVA revealed that scores were significantly different between the attention tasks. Sphericity assumed [$\chi^2(2) = 3.17, p = 0.21$, $F(2, 42) = 87.24$, $p < 0.001$]. The effect size calculated using eta squared was 0.806 and the observed power 1.00. Post-hoc analysis revealed that there was a significant difference between the NBACK and SART task ($p < 0.001$), the NBACK and AVT task ($p < 0.001$) and the SART and AVT tasks ($p < 0.001$). On the basis of the results, we can conclude that the NBACK task (mean score: 32.72 ± 8.08) can be considered a low level attention task for the purpose of this study. The SART (mean score: 49.16 ± 8.92) was considered the medium level attention task with the AVT (Mean Score: 57.61 ± 1.73) being the high level attention task. Figure 1 uses boxplots to show the difference between the tests.

Figure 1: Boxplots of NASA-TLX scores for three attention tasks including post-hoc significance values.

3.2 Upper trapezius muscle activity

The upper trapezius muscle activity was significantly different across the test conditions (Table 1), Wilks lambda=0.289, $F(3,22) = 15.59$, $p < 0.0005$. The partial eta squared = 0.70 and
observed power = 1.00 (Cohen 1988) indicates a large effect or change in upper trapezius muscle activity between tasks. Post hoc analysis revealed that there was a significant difference between the baseline and each attention task (p<0.001). There was a significant difference between the NBACK and the SART tests (p<0.001) and the NBACK and AVT test (p<0.001). A significant difference in muscle activity was not detected between the SART and AVT tasks (p=1.00).

3.3 End-tidal CO₂

Attention tasks had a significant effect on end-tidal CO₂. Wilks Lamda = 0.27, F (3, 19) =11.60, p<0.0001. The partial eta squared =0.73 which indicates a very large effect (Cohen 1988) and the observed power was 0.99. Post-hoc analyses showed a significant difference between the control condition (baseline) and the three attention tests (NBACK: p=0.04, SART: p<0.001, AVT: p<0.001). There were also significant differences between the three attention tasks (NBACK & SART: p<0.001), (NBACK & AVT: p=0.007), (SART & AVT: p=0.007).

3.4 Moderation analysis

The results of a multiple regression moderation model in which the effect of mental workload on upper trapezius muscle activity is moderated by end-tidal CO₂ are shown in Table 2. The moderation models for the NBACK and AVT tasks were statistically significant at the p<0.05 level and at the p<0.01 level for the SART task. Both mental workload (b=0.45 95% C.I.(0.4328, 6.7571), t=2.3, p=0.03) and PetCO₂ (b=0.5 95% C.I. (0.7293, 14.0203), t=2.39, p=0.03) are shown to be significant predictors of upper trapezius muscle activity. Moderation is shown by the significant interaction effect between mental workload and end-tidal CO₂, b= -0.12 CI(-0.2086, -0.0160), t =-2.18, p<0.004 indicating that the relationship between mental workload and upper trapezius muscle activity is moderated by PetCO₂.
Table 2: Regression model coefficients of upper trapezius muscle activity for attention tests

<table>
<thead>
<tr>
<th></th>
<th>NBACK</th>
<th>SART</th>
<th>AVT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>-15.19</td>
<td>207.01</td>
<td>183.09</td>
</tr>
<tr>
<td>SE b</td>
<td>7.15</td>
<td>103.3</td>
<td>100.91</td>
</tr>
<tr>
<td>t</td>
<td>-2.12</td>
<td>-2.04</td>
<td>-1.81</td>
</tr>
<tr>
<td>p</td>
<td>0.48</td>
<td>0.06</td>
<td>0.09</td>
</tr>
<tr>
<td>PetCO₂</td>
<td>0.5</td>
<td>7.19</td>
<td>6.49</td>
</tr>
<tr>
<td>SE b</td>
<td>0.21</td>
<td>3.15</td>
<td>3.08</td>
</tr>
<tr>
<td>t</td>
<td>2.39</td>
<td>2.29</td>
<td>2.1</td>
</tr>
<tr>
<td>p</td>
<td>0.03</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>Mental workload</td>
<td>0.45</td>
<td>3.52</td>
<td>3.2</td>
</tr>
<tr>
<td>SE b</td>
<td>0.19</td>
<td>1.5</td>
<td>1.48</td>
</tr>
<tr>
<td>t</td>
<td>2.3</td>
<td>2.34</td>
<td>2.15</td>
</tr>
<tr>
<td>p</td>
<td>0.03</td>
<td>0.03</td>
<td>0.05</td>
</tr>
<tr>
<td>Mental workload X End-tidal CO₂</td>
<td>-0.12</td>
<td>-0.11</td>
<td>-0.1</td>
</tr>
<tr>
<td>SE b</td>
<td>0.01</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>t</td>
<td>-2.18</td>
<td>-2.4</td>
<td>-2.22</td>
</tr>
<tr>
<td>p</td>
<td>0.04</td>
<td>0.03</td>
<td>0.04</td>
</tr>
</tbody>
</table>

The $R^2$ values for the overall models (Table 3) show that 37% of the upper trapezius muscle activity variance in the NBACK, 26% in the SART and 44% in the AVT models are predicted by variance in mental workload and PetCO₂.

The $R^2$ interaction value shows that 17% of the variance within the NBACK, 24% for SART and 30% for AVT models, was attributable to the interaction between mental workload and end-tidal CO₂. In other words, 45% (0.17/0.37), 92% (0.24/0.26), and 68% (0.3/0.44) of the variance for the upper trapezius muscle activity in NBACK, SART and AVT models respectively is statistically attributable to the moderation effects of end-tidal CO₂.

Table 3: $R^2$ values for moderation model for each attention task.

<table>
<thead>
<tr>
<th></th>
<th>Model $R^2$</th>
<th>P-Value</th>
<th>Interaction (Mental Workload &amp; PetCO₂ $R^2$)</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>NBACK</td>
<td>0.37</td>
<td>0.04</td>
<td>0.17</td>
<td>0.04</td>
</tr>
<tr>
<td>SART</td>
<td>0.26</td>
<td>0.10</td>
<td>0.24</td>
<td>0.03</td>
</tr>
<tr>
<td>AVT</td>
<td>0.44</td>
<td>0.01</td>
<td>0.3</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Figures 2-4 plot the conditional effect or ‘simple slope’ of mental workload at three levels (low, medium and high) of end-tidal CO₂ by using the estimated coefficients from the model for the three attention tasks. Separate regression lines were plotted for low levels of PetCO₂.
(one standard deviation below the mean), medium levels of PetCO$_2$ (PetCO$_2$ mean), and one standard deviation above the mean (Cohen et al. 2003).

The plots give a graphical representation of the relationship between mental workload and upper trapezius muscle activity at three levels of the moderator. It is evident from the plots that at lower levels of end-tidal CO$_2$ (<31 mmHg), the relationship between the other two variables is clearly positive and higher levels of upper trapezius muscle activity are related to higher mental workload scores. There is also a positive relationship with average levels of end-tidal CO$_2$ (31-35 mmHg) and the relationship appears to be negative when end-tidal CO$_2$ levels are high (>35mmHg). We further investigated this interaction using the Johnson-Neyman technique (Hayes 2013). This technique mathematically derives the regions of significance for the conditional effect of mental workload on end-tidal CO$_2$, or the values within the range of the moderator in which the association between mental workload and upper trapezius muscle activity is statistically different from zero. The results are summarised in Table 3. The results show that below the moderator values of 33.76 mmHg, 34.76 mmHg and 33.74 mmHg for the low, medium and high level attention tasks respectively, the models showed statistically significant conditional effects of mental workload for each task. These values are consistent with the hypocapnic range of hyperventilation of < 35 mmHg. A Johnson-Neyman plot depicts the conditional effect of mental workload on upper trapezius muscle activity at the 95% C.I. upper limit, the 95% C.I. lower limit and the point estimate for the moderator when the data from the three attention tasks are combined (Figure 5). The plot shows that at or below 32.59 mmHg, end-tidal CO$_2$ significantly moderates the relationship between mental workload and upper trapezius muscle activity for the combined study data. Above the level of significance, mental workload does not increase muscle activity. We can deduce from figure 5 that the higher the mental workload, the more strongly end-tidal CO$_2$ predicts an increase in upper trapezius muscle activity.
Figure 2: Simple slopes analysis for NBACK attention task
Figure 3: Simple slopes analysis for SART attention task
Figure 4: Simple slopes analysis for AVT attention task

Table 4 lists the values at which PetCO$_2$ started to significantly moderate (P=0.05) the relationship between attention related mental workload and upper trapezius muscle activity for each task. The combined test data is given where data from the three tests were run together in one model.
Table 4: Moderator values (PetCO₂) defining Johnson-Neyman significance region (p=0.05)

<table>
<thead>
<tr>
<th></th>
<th>PetCO₂ (mmHg)</th>
<th>% Participants below J-N significance region</th>
<th>% Participants above J-N significance region</th>
</tr>
</thead>
<tbody>
<tr>
<td>NBACK (n=22)</td>
<td>33.76</td>
<td>57.14</td>
<td>42.85</td>
</tr>
<tr>
<td>SART (n=22)</td>
<td>34.76</td>
<td>68.18</td>
<td>31.81</td>
</tr>
<tr>
<td>AVT (n=22)</td>
<td>33.74</td>
<td>63.63</td>
<td>36.36</td>
</tr>
<tr>
<td>Combined test data (n=66)</td>
<td>32.59</td>
<td>56.06</td>
<td>43.94</td>
</tr>
</tbody>
</table>
Figure 5: Johnson-Neyman plot for combined test data (three attention tests) with conditional effects of mental workload on upper trapezius muscle activity plotted on the y-axis.
4.0 Discussion

4.1 Resting Upper Trapezius Electromyography

Increases in resting trapezius EMG activity from baseline were evident as sustained attention increased. The findings indicate that the attention tasks induced psychosocial stress in the participants thereby altering the physiological activity of the trapezius muscles. Muscle activity increased with increased level of sustained attention required as measured via the NASA-TLX. As the non-dominant arm remained stationary during the experiment and neutral postures were maintained consistently, increases in muscular activity could not be attributed to additional biomechanical demands. Melin (1997) postulated that psychological stress induces low levels of muscle tension, keeping the small motor units active on a continuous basis even when these muscles get periodic breaks from physical work. Based on previous studies, the muscle activity detected is likely to be Type 1 muscle fibre activity.

Hypotheses such as the Cinderella hypothesis (1991) and Henneman size principle (1965) suggest an overload of Type 1 muscle fibres in low static contraction, and these have been associated with occupational static loads (Larsson et al. 1988, SØGaard 1995, Lundberg et al. 2002). Many studies have found that psychological stress and elevated mental workload may cause increases in muscular activity (Lundberg et al. 1994, Waersted and Westgaard 1996, Bongers et al. 1993, Woersted et al. 1993, Vollestad 1993) and as a result increase the risk of muscle fatigue and discomfort (Westgaard and Bjørklund 1987, Mehta et al. 2012, Mehta and Agnew 2012). Sustained increases in muscular activity and tension have been identified as a contributor to WRMSDs (Griffiths et al. 2011, Lundberg et al. 1999, Lundberg et al. 2002, Visser et al. 2004, Bongers et al. 2006, Schleifer et al. 2008). Previous studies report a relationship between stress and muscular activity (Schleifer et al. 2008, Wijsman et al. 2013) but the present study was distinct in its focus on attention-specific tasks as opposed to more typical cognitive stress tests e.g. Stroop test (Stroop 1935).

4.2 End-tidal CO₂

Decreases in end-tidal CO₂ were evident as the participants moved from the baseline condition to the low-level attention task, and further decreases were observed as the medium and high level attention tasks were completed. Decreases in end-tidal CO₂ were also consistent with increases in trapezius muscle activity. This result supports hypothesis 1. It has been suggested that the relationship between end-tidal CO₂ and muscle functioning is two-fold. Hyperventilation or overbreathing firstly imposes a biomechanical load on the
neck-shoulde as a result of activating the sternocleidomastoid, scane, and trapezius
muscles in support of thoracic breathing under stress (Hall 2010). Secondly, hyperventilation
as a result of stress results in a decrease in the proportion of CO₂ in blood and a subsequent
rise in blood pH (respiratory alkalosis) (Lum 1976). This change in pH increases the
likelihood of motor unit activation. The second hypothesis queried if the relationship between
mental workload and upper trapezius muscle activity depended on levels of end-tidal CO₂.
The moderation model supported hypothesis 2 by proving that end-tidal CO₂ moderated the
relationship between sustained attention and upper trapezius muscle activity for each
attention test at values below 35 mmHg. Most medical sources define hypocapnia as less than
35 mmHg for partial CO₂ pressure in the arterial blood (Oakes 2008). The model is therefore
useful as it proves that increased levels of attention-related mental workload can lead to
elevated upper trapezius muscle activity through hypocapnic hyperventilation conditions. It
has been proposed previously that a relationship exists between stress induced
hyperventilation and musculoskeletal disorders at work (Ley 1995, Ley and Ley 1996,
Schleifer and Ley 1994a, Schleifer et al. 2008). Our model further informs this established
relationship by defining the arterial end-tidal CO₂ conditions necessary for sustained attention
tasks to contribute to muscular activity.

Our results further support the attentional resource model of sustained attention. The attention
tasks, including the SART task which contrary to promoting mindlessness as it was designed
to do, elicited a physiological stress response which is consistent with the view that attention
tasks require high mental workload and are stressful.

4.3 Implications for Work Design

Organizations should consider sustained attention as a potential risk factor in the
development of WRMSDs and factor this into future job design. Modern approaches to
automation such as adaptive automation, which adapt automated processes to the human
operator should recognise that sustained periods of attention are not beneficial to employee
health. With adaptive automation, both the user and the system can initiate changes in the
levels of automation with the objective of optimal human-machine performance (Sheridan
2011). If more monitoring tasks are shared with the automation, operators will avoid a
sustained increase in low-level muscle activity and potential activation of physiological stress
mechanisms. Using organisational interventions such as job rotation and meditation training
(MacLean et al. 2010) for tasks requiring high levels of sustained attention might represent
testable strategies to reduce the impact of this work on psychophysiological responses.

4.4 Limitations for Practice in Industry

The precise relationship between psychophysiological response and increased risk of
musculoskeletal disorders remains unclear, which is a clear limitation for this study. It is also
acknowledged that using short attention tasks alone is not reflective of a typical workplace
monitoring scenario where operators may have to monitor processes along with carrying out
other tasks over the work shift. A standardised self-report questionnaire tool was used to
check mental workload levels of the tests employed which might influence the outcome due
to individual reporting bias (Adams et al. 1999). Gender differences were not determined due
to insufficient power to run the moderation model within the smaller gender groups.

5.0 Conclusions

This study supplements current research in providing a statistically significant moderation
model that supports the existence of a relationship between attention tasks and muscular
activity when end-tidal CO$_2$ values are in the hypocapnic range. This is the first research
study that has provided evidence of this moderated relationship. We can also conclude that
increases in sustained attention resulted in an elevated psychophysiological stress response
and it can therefore be considered a psychosocial stressor (Cox et al. 2000, Warm et al. 2008,
Szalma et al. 2004, Helton et al. 2010). We can deduce from these results that the intensive
monitoring component of operator roles in modern manufacturing is likely to contribute via
an increase in sustained muscular activity to the development of WRMSDs.

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