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Effect of varying levels of mental workload on startle eyeblink modulation

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Abstract

Previous research using punctuate reaction time and counting tasks has found that the startle eyeblink reflex is sensitive to attentional demands. The present experiment explored whether startle eyeblink is also modulated during a complex continuous task and is sensitive to different levels of mental workload. Participants ($N = 14$) performed a visual horizontal tracking task either alone (single-task condition) or in combination with a visual gauge monitoring task (multiple-task condition) for three minutes. On some task trials, the startle eyeblink reflex was elicited by a noise burst. Results showed that startle eyeblink was attenuated during both tasks and that the attenuation was greater during the multiple-task condition than during the single-task condition. Subjective ratings, endogenous eyeblink rate, heart period, and heart period variability provided convergent validity of the workload manipulations. The findings suggest that the startle eyeblink is sensitive to the workload demands associated with a continuous visual task. The application of startle eyeblink modulation as a workload metric and the possibility that it may be diagnostic of workload demands in different stimulus modalities is discussed.

1. Introduction

The concept of mental workload is often applied when researchers investigate the information processing demands placed on operators as they interact with machines. Specifically, mental workload refers to the amount of the operators limited processing capacity that is needed to perform a given task (O'Donnel and Eggemeier 1986). Mental workload assessment is an important issue in research and development because excessively high or low levels of workload can lead to errors and system failure. Researchers have examined potential workload measures from different classes, including subjective, performance, analytic, and physiological (for a review see Tsang and Wilson 1997). Unfortunately, no one measure has proven to be the golden yardstick of mental workload. The construct of mental workload appears to be too multidimensional to be adequately captured by a single measure. The future advancement of workload assessment lies in research that develops a variety of measures with well-known properties. The present research aimed to explore a possible new physiological measure of mental workload that may possess unique properties in comparison to other measures. This new measure is the startle eyeblink reflex.

The startle reflex is a complex of responses that follows the presentation of an abrupt and moderately intense stimulus. In humans, the most reliable component of the startle response is the eyeblink, and researchers can record startle eyeblinks by measuring the activity of the orbicularis oculi muscle surrounding the eye via electromyographic (EMG) recordings. Figure 1 shows the typical electrode placement and the resulting raw EMG signal associated with a startle eyeblink response. The response is commonly quantified by measuring the magnitude and latency of the elicited eyeblink. The eyeblink can be elicited by intense and abrupt stimuli from a number of input modalities, such as a burst of noise, a flash of light, or a tap to the forehead. In and of itself, the startle eyeblink is of limited

interest for psychologists. Rather, it is the modification of the eyeblink reflex by changes in the sensory environment or concurrent cognitive processes that has stimulated extensive research (for a review see Dawson et al. 1999). This has led to the development of the startle probe methodology - changes in the startle eyeblink relative to a control condition are used to index cognitive processes. The startle probe methodology has been applied to the study of emotion, sensory gating, and attention (Dawson et al. 1999). In recent years, it has been increasingly applied to the study of psychopathologies such as schizophrenia and depression and in the study of developmental processes. However, the potential of the startle methodology as a probe for workload demands during complex real world tasks has not yet been assessed. This is surprising because as a probe the startle eyeblink offers several advantages. For instance, startle eyeblink reflexes do not demand attention and do not require compliance from the participant. In addition, because the latency of the startle eyeblink is in the range of 20 to 70 ms (Berg and Balaban 1999), it possesses good temporal resolution of cognitive activity. Finally, the startle eyeblink may be diagnostic of mental workload demands associated with different stimulus modalities.

[Insert figure 1 about here]

From early on in the investigation of the startle eyeblink reflex, it became clear that it is sensitive to attentional processes. Graham et al. (1975) reported findings that showed a link between startle facilitation and anticipatory orienting as reflected in heart rate deceleration. These findings suggested that facilitation of sensory processing may result in the enhancement of the startle response (Putnam 1990). To investigate the role of selective attention in startle eyeblink modification further, Anthony and Putnam conducted a series of experiments in which the nature of the experimental stimuli and tasks were varied (see Putnam 1990). The experiments required a voluntary reaction time response or an involuntary startle response at the end of a 6 s warning stimulus. The time course of startle

eyeblick modification was examined by presenting an acoustic startle probe at various times during the warning stimuli. In some experiments, a modality match condition was used in which the warning stimulus was presented in the same modality as the startle probe (i.e. both were acoustic). In other experiments, a modality mismatch condition was used in which the warning stimulus was presented in an orthogonal modality to the startle probe (i.e. visual warning stimulus and acoustic probe). The results showed that startle eyeblink was facilitated during the modality match condition. Startle eyeblink was inhibited, however, during the modality mismatch condition. Moreover, the extent of startle inhibition and facilitation during each condition increased towards the end of the warning stimulus and hence the occurrence of the imperative task or stimulus. The results suggest that the startle eyeblink response is sensitive to the direction of and to the amount of attention allocated during a simple short duration stimulus.

The effects of selective attention on startle eyeblink modification have been observed in other research (Putnam 1990, Hoffman 1997). It is important to note from this research that the tasks used have tended to be relatively simple punctuate tasks: the imperative stimuli are only presented for a short duration and participants are required to perform a relatively simple task. For instance, startle eyeblink facilitation during a modality match condition has been observed when participants are required to perform a counting task (Jennings *et al.* 1996), an attention-focussing discrimination task (Bohlin and Graham 1977), or when passively viewing pictures (Anthony and Graham 1985). Attenuated startle during modality mismatch conditions has also been observed during a passive viewing (Anthony and Graham 1985) and a visual search (Shicatano and Blumenthal 1998) task (but see Lipp *et al.* 2000). Taken together, the previous research provides a theoretical basis to suggest that startle eyeblink modification will be sensitive to the attentional demands of a complex continuous task and that it may also be sensitive to the stimulus modality that attention is directed

towards. The latter possibility has important implications for the issue of diagnosticity of workload metrics, at least along the dimension of input modality (Wickens 1987). However, before this issue can be examined, a demonstration of the sensitivity of the startle eyeblink reflex to different levels of mental workload demands is needed.

The present study aimed to explore the sensitivity of startle eyeblink modification to mental workload demands during a continuous visual task. Participants were asked to perform a tracking task for 180 s either alone (single-task condition) or in combination with a visual gauge monitoring task (multiple-task condition). The startle eyeblink to an acoustic probe was measured during the tasks to assess the differences in eyeblink modification to a baseline (no-task) control condition and to assess whether eyeblink modification was differentially sensitive to the level of workload associated with the tasks. Because the tasks to be performed were primarily visual, it was hypothesised that the startle eyeblink would be attenuated when participants performed the tasks and that the attenuation would be greater in the multiple-task condition than in the single-task condition. Converging validity of the workload manipulations was obtained by assessing self-reported ratings and by measuring endogenous eyeblink rate, heart period, and heart period variability (see Tsang and Wilson 1997 for a review of these measures). Previous research has found that endogenous eyeblink rate is reduced during a multiple-task condition relative to a single-task condition (Sirevaag *et al.* 1988). Heart period tends to be shorter during conditions of high workload (e.g. Veltman and Gaillard 1998). Heart period variability is often calculated through spectral analysis. The analysis decomposes variability into different frequency regions: a very low frequency region (0.03 to 0.05 Hz) thought to reflect temperature regulation, a low frequency region (0.05 to 0.15 Hz) thought to reflect blood pressure regulation, and a high frequency region (0.15 to 0.4 Hz) thought to reflect respiratory influences. Mental workload can reduce power

in all frequency regions (Egelund 1982, Veltman and Gaillard 1998), although it tends to have the largest effect in the low frequency band (Aasman et al. 1987).

Two further issues were examined in the present study. The first was related to the fact that the startle probe elicits an eyeblink response that is involuntary and as such could be disrupting. It is possible that the presentations of the startle probe might impair task performance and interfere with the measurements obtained from other workload metrics. This concern is not unique to startle probe methodology, but is shared with other probe-based measures of mental workload such as secondary task reaction time and event-related evoked potentials (Tsang and Wilson 1997). Participants thus performed in task conditions that did and did not contain startle probes. If the startle probe methodology is intrusive, the conditions that contain the startle probe will be associated with impaired task performance and will be less likely to obtain effects of mental workload on endogenous eyeblink rate, heart period, heart period variability, and subjective ratings. The second issue examined concerned habituation of the startle eyeblink. Previous research consistently shows that startle eyeblinks diminish in size and become longer in latency with repeated presentations of the startle probe. Habituation of the startle reflex has shown to influence sensory gating processes, as assessed by prepulse inhibition (Lipp and Krinitzky 1998). It is also possible that habituation may interact with attentional modulation of the startle eyeblink reflex. To examine this issue, the extent of habituation was assessed by measuring startle eyeblinks in baseline trials before and after the experiment and by presenting repeated trials of each workload condition. Although it was expected that the startle eyeblink would habituate, this effect was not expected to interact with the modification of startle eyeblinks caused by the workload manipulations.

2. Method

2.1. Participants

Three males and eleven females, with a mean age of 27.89 years (range = 18.42 to 49.72 years), were recruited from the staff at the University of Western Australia, Australia (3 participants) and through advertisements in the local community (11 participants).

Participants recruited through advertisement were paid AUS\$20.00 for participation. The participants had a mean education level of 14.75 years (range 12 to 19 years) and interacted with a computer for an average of 32.15 hours per week (range 15 to 50). All participants were right handed, had normal or corrected to normal vision and hearing, and did not have a history of psychiatric or neurological illness. Testing lasted about 130 min and each participant provided informed consent prior to participation.

2.2. Apparatus

2.2.1. Physiological response measurement. Startle eyeblink and endogenous eyeblink were measured via EMG recordings of the orbicularis oculi eye muscle using two 6 mm platinum coated Electrocap E-21 electrodes filled with Ten20 conductive electrolyte. One electrode was placed 10 mm under the pupil of the left eye and the second was placed 10 mm lateral. A Fastrace 4 disposable Ag/AgCl tab electrode in conjunction with an Electrode Store ETL electrode clip was placed on the participants left forearm as the ground electrode. The raw EMG signal was amplified with a Grass CP511 AC preamplifier using a high and low-pass cut-off of 100 Hz and 1 kHz respectively and with amplification set at 50,000. Heart period was measured via electrocardiographic (EKG) recordings using three Fastrace 4 disposable Ag/AgCl tab electrodes with Electrode Store ETL electrode clips. Two electrodes were placed over the sternum (one over the manubrium and the second over the xiphoid process) and the ground electrode was placed on the inside right forearm. A Grass CP511 AC preamplifier using a high and low-pass cut-off of 10 and 100 Hz respectively was used to

amplify the raw EKG signal. The raw EMG and EKG signals were digitised and sampled on-line via a National Instruments AT MIO 16E10 multifunction I/O board using a sampling rate of 1000 Hz.

The startle eyeblink was elicited by a 100 dBA burst of white noise of 50 ms duration and presented with an instantaneous rise time. The startle probe stimulus was presented over a 60 dBA continuous background white noise. All acoustic stimuli were presented through Arista LS400 Dynamic Stereo Headphones encased in Bilson Viking 2421 housing to further dampen possible distracting environmental noise.

2.2.2. Task apparatus and stimuli. The experiment was completed in a sound attenuated room in which the experimenter sat behind and to the right of the participant. A Compaq DeskproTM computer running the National Instruments LabViewTM (version 4.1) program controlled data acquisition and stimulus presentation throughout the experiment. The task interface was a custom written program and was displayed on a Compaq P50 computer monitor placed approximately 120 cm from the participant at eye level. The computer screen was divided horizontally in two halves (see figure 2). The top half consisted of a horizontal tracking task (subtending $0.5^\circ \times 9.5^\circ$ visual angle). The bottom half consisted of a gauge monitoring task (subtending $3.3^\circ \times 12.6^\circ$ visual angle) and employed four vertical gauges on the left and two dial gauges to the right of the display (subtending $5.2^\circ \times 3.3^\circ$ and $5.7^\circ \times 3.3^\circ$ visual angle respectively). During the trial, the computer controlled the movements of the indicators according to a predetermined set of algorithms. Each indicator could change its value every 50 ms during the trial.

[Insert figure 2 about here]

In the horizontal tracking task, the computer controlled a cross that moved along a horizontal scale. The cross, subtending 0.3° visual angle, moved to the next point to the left, to the right, or remained at the same location with equal probability throughout the trial.

Participants were required to use a FlightStick Pro joystick (product FS224) with their left hand to control the movement of a circle, subtending 0.5° visual angle, along the horizontal line. Participants were instructed to keep the circle around the cross all times during the trial.

In the gauge-monitoring task, the participants were required to simultaneously monitor each of the vertical and dial gauges. For the vertical gauges the pointer moved up and down the scale until it fell within the dark region at the top of the scale. If the pointer moved within the dark region, it was unable to move down and out of this region.

Participants were asked to monitor the vertical gauges, each subtending $0.9^\circ \times 3.1^\circ$ visual angle, and detect when the pointer moved within the dark region. If the pointer moved within this region, the participants were to operate a mouse with their right hand to reset the gauge. The gauge was reset by moving the cursor over the RESET button (subtending $1^\circ \times 0.5^\circ$ visual angle) below the faulty gauge and clicking the mouse button. The pointer was then reset to the minimum value. An algorithm varied the speed with which the pointer moved up the scale to the critical region. Four different algorithms were used and they were allocated at random without replacement such that one gauge had an average of 1 fault every 180 s, a second had an average of 3 faults, a third had an average of 9 faults, and a fourth had an average of 12 faults. In the dial gauge-monitoring task, the pointer moved about the dark region in the centre of the gauge. Participants were asked to monitor the gauges (each subtending 2.6° visual angle) and detect whenever the pointer fell outside of the dark central region. If the pointer moved outside the region, the participant was to use the mouse and click on the RESET button for the faulty gauge. Once the button was pressed, the pointer was reset to the middle of the dark central region. Identical algorithms were used to control the movements of the dial gauge such that each gauge had an average of 6 faults every 180 s.

2.2.3. Self-reported workload ratings. Self-reported ratings of mental workload demands were obtained by adopting a format used in the modified Cooper-Harper rating

scale (Wierwille and Casali 1983). Participants were initially given a definition of mental effort that followed that used in the Mental Demand subscale of the NASA Task Load Index (Hart and Staveland 1988) and then asked to make a rating of the task demands using the modified Cooper-Harper rating scale. This scale uses a decision tree to lead participants to rate the workload demands between 1 (very easy, highly desirable difficulty) and 10 (impossible difficulty).

2.3. Procedure

After providing informed consent, participants were seated in a comfortable chair and given instructions for the task. Two types of task trials were used with the duration of each being 180 s. In the single-task condition, the participants performed the horizontal tracking task on its own. Although the gauges remained on the computer display, the pointers for each gauge never moved more than one value from the baseline. Participants were asked to ignore any movements of the gauges. In the multiple-task condition, participants performed the horizontal tracking task in addition to the gauge-monitoring task for all the vertical and dial gauges. Participants were instructed to treat the tracking task as primary and to treat the gauge-monitoring task as secondary. Participants were asked to give equal attention to each gauge. Participants were told that performance would be measured by the amount of error in the tracking task and the accuracy and latency of responses in the gauge monitoring task. After the instructions, the participants practised moving the joystick with their left hand and practised moving the mouse button with their right. Next, practice trials for the single-task condition and multiple-task condition were given. Each participant performed the single-task condition first. After a 60 s break, participants performed the multiple-task condition. Performance measures from the practice trials were disregarded and will not be reported.

Once practice was completed, electrodes for the physiological recordings were attached. Next the participant completed two baseline trials to ascertain their baseline level

of physiological responsivity, independent of the tasks. Initially, baseline levels of heart rate and endogenous eyeblinks over a 180 s period were determined by instructing the participant to sit quietly with his or her eyes open. Next, baseline levels of startle eyeblink responses were determined. The 180 s baseline period was divided into six intervals of 30 s duration. A startle probe was presented at random times during each of the six intervals. Heart period and endogenous eyeblink were also recorded. Participants were told that they would hear a noise burst at random times and that they should sit quietly with their eyes open.

After the baseline trials, the experiment proper began. The experiment consisted of a series of 12 trials in which the single-task conditions and the multiple-task conditions were given, such that some trials contained startle probe stimuli and some did not. The trials were arranged into three blocks of four trials, such that each block contained one single-task condition with no startle probes, one single-task condition with startle probes, one multiple-task condition with no startle probes, and one multiple-task condition with startle probes. Order of task conditions within each block was varied at random. In the trial conditions that contained startle probes, the 180 s trial was divided into six intervals of 30 s. The startle probe was presented at a random time during each of the intervals. Participants were given warning as to which task conditions contained startle probe stimuli and which did not. The participants completed the subjective ratings of the workload demands at the completion of each task condition in the first and third trial block. No ratings were made during the second trial block. Each task condition was preceded by a 120 s baseline period during which participants were instructed to rest quietly with their eyes open. The baseline periods were used to ensure that participants did not fatigue during the experiment and to minimise any carryover effects from performance of one trial to the next. Although heart rate and endogenous eyeblinks were recorded during the baseline periods, they are not reported.

After completion of the experiment proper, the participants completed two baseline trials. The same baseline trials as used before the experiment proper were employed, such that the first 180 s baseline period did not contain startle probes and the second baseline period did. After completion of the experiment, the participant was debriefed and, if relevant, given his or her reimbursement.

2.4. Scoring and response definition

The digitised raw EMG activity was rectified offline and integrated using a Butterworth filter set with a time constant of 100 ms. Startle eyeblink magnitude (initially quantified in A/D units and later converted to μV according to the conversion 1 A/D unit = 1.3 μV) and latency (in ms) was obtained from the integrated signal using a sampling window from 100 ms prior to and 200 ms following startle probe onset. Magnitude was defined as the maximum of the integrated signal within 200 ms after startle pulse onset. If the response did not exceed the criterion of 25 μV above the baseline signal, magnitude was scored as zero. Latency was defined as the time at which the response reached two standard deviations above the level of activity during the 100 ms prior to the startle probe onset. Latency was scored as missing if the response magnitude was zero. A trial was scored as missing if either baseline variations exceeded 150 μV within the 100 ms prior to the startle pulse or the onset of the startle eyeblink response was not within 20 to 70 ms after startle pulse onset. Endogenous eyeblinks were also calculated from the integrated EMG signal. The number of eyeblinks was calculated for each of the six 30 s intervals of a 180 s trial. Eyeblinks were identified with a peak detector based on an algorithm that fitted a quadratic polynomial to sequential groups of data points. The number of data points used in each fit was 200 (corresponding to 200 ms) and they overlapped throughout the entire sample. Each quadratic fit was tested against a threshold defined as 3 standard deviations above the mean signal. All responses that did not exceed the criterion of 25 μV above the mean signal were

disregarded. In the trials that included startle probe presentations, the count includes the eyeblinks elicited by the startle probe. Prior to statistical analysis, the number of eyeblinks that occurred during each 30 s interval was doubled to give an eyeblink rate per min. Due to an unstable baseline, it was difficult to reliably score the endogenous eyeblink rate of one participant. This participant was thus excluded from the statistical analyses for this measure.

The processing of the EKG signal for the calculation of heart period used the following method. The EKG signal obtained during each 180 s baseline and task trial was processed using a peak detector for the identification of R-peaks. The interbeat intervals were screened for artefacts and heart period was calculated using time-based methods described by Graham (1978) to derive a value for each successive 0.5 s bin. The resulting heart period data was averaged to derive a mean heart period across each 180 s baseline and task trial. The variability of the heart periods across the successive 0.5 s bins was examined by power spectral analysis using the following method (Stark *et al.* 2000). Initially, the linear trend and mean value were removed from the data. A cosine taper was next applied to reduce the side lobes of the spectrum. To use the fast Fourier transformation, zero padding was employed to ensure that the number of data points was a power of two. The spectral plot derived from the fast Fourier technique was used to calculate the frequency components through the summation of power values inside three frequency boundaries. Power values were calculated for a very low frequency component (0.003 to 0.05 Hz), a low frequency component (0.05 to 0.15 Hz), and a high frequency component (0.15 to 0.4 Hz).

Tracking performance was calculated as the average distance between the indicator (cross) and the participants controller (circle) across the trial. The mean tracking error was used as the performance measure during the single-task condition. A composite Z-score was calculated from the behavioural responses during the multiple-task condition. Initially, the responses to the gauge faults were standardised for each participant by dividing the reaction

times for each gauge by the number of correct responses. A performance score for each gauge type was then calculated by weighting each vertical gauge measure by one quarter and summing or weighting each dial gauge by one half and summing. The final composite performance $\bar{Z}$ -score was then calculated by weighting the tracking task performance score, the summed vertical gauge performance score, and the summed dial gauge performance score by one third and summing them together.

2.5. Statistical analysis

One participant was an outlier due to a high endogenous eyeblink rate in all experimental conditions. Statistical analyses performed with and without this participant yielded identical findings. However, since inclusion of this participant may artificially inflate the means in each condition, the results for endogenous eyeblink rate when this participant was excluded are reported. In addition, the frequency of trials that were scored as missing for startle latency and amplitude were calculated for each task condition and trial block. Missing trials may bias the results if they are more frequent in one task condition than in another (e.g., a bias may result if missing trials are more common under high workload demands). Separate 2 x 3 (Task condition x Trial block) ANOVAs were conducted on the frequency of missing latency and amplitude trials to examine this issue. The analyses yielded no significant differences between the task conditions in any trial block, all $F_s < 1.01$, suggesting that missing trials were not more frequent in any particular task condition. Prior to statistical analyses, the latency and amplitudes for the startle eyeblink responses and the endogenous eyeblink rate during each of the six 30 s intervals of the 180 s baseline and task trials were averaged together. The absolute power values of the three frequency components derived from the power spectral analysis were log-transformed prior to statistical analysis to normalise the distributions.

To determine whether endogenous eyeblink rate, heart period, and heart period variability were significantly modified during the task conditions, the pre-task and post-task baseline trials were averaged and compared with an average across the task trials using separate 2 x 2 (Trial type x Startle presence) ANOVAs. Changes in the baseline level of responding across the experiment were also examined by comparing responding between the pre-test and post-test baseline trials with separate 2 x 2 (Baseline trial x Startle presence) ANOVAs. Similar analyses of the modification during the task conditions and in baseline level of responding were performed with startle amplitude and latency although *t*-tests were used since only those baseline and task trials that measured startle eyeblinks were compared.

Subjective ratings of the workload demands associated with the tasks were examined with a 2 x 2 x 2 (Task condition x Startle presence x Trial block) ANOVA. Differences between task conditions for the tracking task performance, endogenous eyeblink rate, heart period, and heart period variability, were examined with separate 2 x 2 x 3 (Task condition x Startle presence x Trial block) ANOVAs. Startle amplitude and latency modulation was examined only on those task trials that contained startle probes. As a consequence, the startle data were examined with separate 2 x 3 (Task condition x Trial block) ANOVAs. Similarly, the composite task *Z*-score was examined only during the multiple-task condition using a 2 x 3 (Startle presence x Trial block) ANOVA.

For all analyses, Greenhouse Geisser adjusted degrees of freedom were used for analyses that included within-participant factors of more than two levels. Post hoc multiple comparisons between means were made with *t*-tests. The critical values for the *t*-tests were derived from Sidak's tables to protect against the accumulation of α -error (Rohlf and Sokal 1981). The level of significance was set at .05 for all statistical analyses.

3. Results

3.1. Startle eyeblink modification

Figure 3 shows startle latency (top panel) and startle magnitude (bottom panel) during the pre-task and post-task baseline conditions and during the single and multiple-task conditions in each trial block. As can be seen, startle latency during the pre-test baseline did not differ from startle latency during the post-experiment baseline, $t(13) < 1$. However, startle magnitude showed a significant habituation effect. Startle magnitude during the pre-test baseline was significantly larger than startle magnitude during the post-test baseline, $t(13) = 5.46$. Startle latency during the combined task trials was significantly slowed relative to the combined baseline trials, $t(13) = 3.71$. Similar results were found with startle magnitude modulation, with smaller eyeblink responses during the task trials than during the baseline trials, $t(13) = 4.75$.

[Insert figure 3 about here]

As shown in figure 3, startle eyeblink was longer in latency and smaller in magnitude during the multiple-task condition than during the single-task condition. This effect for startle latency was confirmed by a main effect for Task condition, $F(1,13) = 8.83$, $MSE = 15.34$. A main effect for Trial block was also found, $F(2,26) = 4.11$, $MSE = 2.67$, and indicated that latency was slower in Block 3 than in Block 1, $t(26) = 2.59$, but there was no difference in the other trial blocks, all $ts < 2.09$. The Task condition x Trial block interaction was not significant for startle latency, $F < 1$. The differences between task conditions in startle magnitude were substantiated by a main effect for Task condition, $F(1,13) = 14.31$, $MSE = 1240$. However, there was also a main effect for Trial block $F(2,26) = 28.01$, $MSE = 352$, and a Task condition x Trial Block interaction $F(2, 26) = 4.84$, $MSE = 318$. The source of the interaction was due to startle magnitude decreasing across blocks in the single-task condition (1 vs. 2, $t(26) = 4.10$, 2 vs. 3, $t(26) = 3.20$), but not during the multiple-task condition (1 vs.

2 $t(26) = 0.81$; 2 vs. 3 $t(26) = 2.31$, both $ps > .05$). The interaction was not due to a failure to find differences between the single-task and multiple-task conditions in one of the trial blocks because the difference between the conditions in Block 3 (the smallest of the differences) was still reliable using α corrected t -values, $t(26) = 2.63$.

3.2. Endogenous eyeblink rate

Table 1 shows the endogenous eyeblink rate, heart period, and the measures of heart period variability during the baseline and task conditions that did and did not contain the startle probe. The endogenous eyeblink rate during the pre-test baseline condition tended to be lower than during the post-test baseline condition. However, the main effect for Baseline trial failed to reach statistical significance, $F(1,11) = 4.51$, $MSE = 4.41$, $p = .057$. The analyses involving the Startle presence factor were not significant, $F < 1$. Endogenous eyeblink rate was significantly reduced during the task trials relative to the baseline trials as indicated by a main effect for Trial type, $F(1,11) = 25.57$, $MSE = 5.62$. The main effect and interaction involving the Startle presence factor were not significant, $F_s < 2.09$.

[Insert table 1 about here]

Endogenous eyeblink rate during the task conditions differed as a function of the type of task and the presence of the startle probe. A main effect for Task condition, $F(1,11) = 9.37$, $MSE = 4.70$, confirmed that eyeblink rate was reduced during the multiple-task condition relative to the single-task condition. In addition, a main effect for Startle presence, $F(1,11) = 15.81$, $MSE = 1.44$, indicated that eyeblink rate was higher in those conditions that contained a startle probe than in those conditions that did not. No other main effects or interactions reached statistical significance, all $F_s < 3.06$.

3.3. Heart period

Analyses of mean heart period during the pre-task and post-task baseline trials yielded no significant effects, all $F_s < 3.35$. Heart period during the baseline trials, however, was

longer than during the task trials, as indicated by a Main effect for Task condition, $F(1,13) = 30.25$, $MSE = 256.38$. The presentation of the startle probe had no effect on heart period and did not interact with task condition, $F_s < 3.04$.

The statistical analyses during the task trials showed that mean heart period was shorter during the multiple-task condition than during the single-task condition, as substantiated by a Main effect for Task condition, $F(1,13) = 7.33$, $MSE = 1267$. A main effect for Trial block was also found, $F(2,26) = 4.55$, $MSE = 971$. The main effect was due to heart period being shorter in Block 1 than in Block 3, $t(26) = 2.85$, whereas all other comparisons were not significant, all $t_s < 1.51$.

3.4. Heart period variability

Statistical analyses of the very low frequency band during the baseline trials yielded a Main effect for Baseline trial, $F(1,13) = 10.36$, $MSE = 0.06$, and indicated that power was lower during the pre-test baseline than during the post-test baseline. The effects involving the startle presence factor were not significant, $F < 1$. Analyses of the low frequency component showed that power varied as function of both Baseline trial and Startle presence, $F(1,13) = 5.14$, $MSE = 0.03$. The interaction was due to power being lower on the pre-task baseline trial that contained the startle probe than on the pre-task baseline trial that did not contain the startle probe, $t(13) = 3.07$. The difference between the post-task baseline trials that did and did not contain the startle probe was not significant, $t < 1$. The main effect for Baseline trial and Startle presence were not significant at the preset level, $F_s < 4.12$. The analyses of the high frequency component during the baseline trials yielded no significant main effects or interactions, all $F_s < 3.89$.

Similar to the mean heart period data, the heart period variability was significantly modified by the requirement to perform a task. Power in the very low frequency band was smaller during the task trials than during the baseline trials, as substantiated by a Main effect

for Trial type, $F(1,13) = 22.65$, $MSE = 0.04$. The main effect and interaction involving the Startle presence factor were not significant, $F < 2.23$. Analyses of the low frequency component yielded a Main effect for Trial type, $F(1,13) = 22.63$, $MSE = 0.05$, a Main effect for Startle presence, $F(1,13) = 4.88$, $MSE = 0.02$, and a Trial type x Startle presence interaction, $F(1,13) = 10.04$, $MSE = 0.02$. The interaction was due to lower power in the baseline trial that contained the startle probe than in the baseline trial that did not, $t(13) = 3.74$. The difference between the task trials that did and did not contain the startle probe was not significant, $t < 1$. The results for the high frequency component showed that power was smaller during the task conditions than during the baseline conditions, as substantiated by a Main effect for Trial type, $F(1,13) = 25.80$, $MSE = 0.03$. A Main effect for Startle presence was also found, $F(1,13) = 5.36$, $MSE = 0.02$, and indicated that power was lower when the startle probe was presented than when the probe was not presented. The Trial type x Startle presence interaction was not significant, $F < 1.03$.

Table 1 shows that the multiple-task condition was associated with less power in each of the frequency bands than the single-task condition, regardless of the presence or absence of the startle probe. This impression was confirmed by the statistical analyses. The analyses for the very low frequency component yielded a Main effect for Task condition, $F(1,13) = 7.69$, $MSE = 0.07$, whereas the Main effect for Startle presence approached significance, $F(1,13) = 4.52$, $MSE = 0.03$, $p = 0.053$. No other main effects or interactions reach significance, all $F_s < 2.63$. The differences between the task conditions in the low frequency component were substantiated by a Main effect for Task condition, $F(1,13) = 14.42$, $MSE = 0.05$, whereas no other comparisons were reliable, all $F_s < 1.63$. Similarly, power in the high frequency band was smaller during the multiple-task condition than during the single-task condition, $F(1,13) = 20.35$, $MSE = 0.05$, whereas all other comparisons were not significant, all $F_s < 2.28$.

3.5. Subjective workload ratings

The workload ratings, as shown in table 2, confirmed that the subjective workload demands were greater during the multiple-task condition than during the single-task condition. The analyses yielded main effects for Task condition, $F(1,13) = 26.35$, $MSE = 3.25$, a Task condition x Startle presence interaction, $F(1,13) = 5.35$, $MSE = .327$, and a Task condition x Startle presence x Trial block interaction, $F(1,13) = 6.07$, $MSE = .288$. Post hoc comparisons of the 3-way interaction compared ratings as a function of startle presence or absence separately for each task condition and trial block. The analysis revealed that the comparison between the single-task/no startle condition and the single-task/with startle condition was significant in Block 3, $t(13) = 2.86$, whereas there was no difference in Block 1, $t < 1$. Contrary to expectations, this comparison suggested that the tracking task imposed less workload demands when there were presentations of the startle probe than when the startle probe was not presented. No comparisons for the multiple-task conditions were significant, all $t_s < 2.14$.

[Insert table 2 about here]

3.6. Task performance

The participants performance of the tracking task during the single-task and multiple-task conditions is shown in table 3. As can be seen, performance of the tracking task was poorer during the multiple-task condition than during the single-task condition, as substantiated by a main effect for Task condition, $F(1,13) = 54.11$, $MSE = .79$, and a Task condition x Trial block interaction $F(2,26) = 7.23$, $MSE = .112$. The interaction was examined by comparing performance across blocks separately for each task condition. The analyses showed that there was significantly less tracking error in Block 2 than in Block 3 for the multiple task condition, $t(26) = 3.60$, whereas all other comparisons between trial blocks were not significant, all $t_s < 1.70$. The presentation of the startle probe did not affect tracking

performance, as indicated by the failure for all main effects and interactions involving the Startle presence factor to reach significance, all $F_s < 1$. Likewise, performance during the multiple-task conditions, as assessed by the composite task score (see table 3), did not differ depending on whether the startle probe was or was not presented. Indeed, performance remained stable throughout the experiment, all $F_s < 1.50$.

[Insert table 3 about here]

4. Discussion

The present experiment showed that modulation of the startle eyeblink reflex is sensitive to the mental workload demands of a complex continuous task. The requirement to perform a continuous visual task was associated with attenuated startle eyeblinks relative to a no-task baseline condition. Moreover, the attenuation of startle eyeblink was greater during the multiple-task condition than during the single-task condition. Convergent validity that the mental workload demands were greater during the multiple-task condition than during the single-task condition was obtained with subjective ratings and other physiological measures. Endogenous eyeblink rate, heart period, and heart period variability all showed a greater reduction during the multiple-task condition than during the single-task condition. Performance on the tracking task also indicated that mental workload demands were greater during the multiple-task condition than during the single-task condition.

The present findings extend previous studies of startle eyeblink modulation that have used relatively simple and punctuate tasks. Consistent with the previous research that have used simple visual tasks (e.g. Anthony and Graham 1985, Shicatano and Blumenthal 1998), the present research found that acoustic elicited startle eyeblinks were attenuated during a complex continuous visual task. Attenuation was observed in both startle eyeblink latency and amplitude, although habituation effects complicated the attenuation of the latter measure. To account for habituation, the pre-test and post-test baseline trials were averaged together

and compared with startle magnitude during the task trials. A more rigorous methodology might intersperse baseline trials across the task trials in a counterbalanced fashion between participants. Nevertheless, the findings are significant because they indicate that the startle eyeblink is inhibited when sustained attention is allocated to the visual modality, as predicted by modality specific accounts of attentional startle modulation (Putnam 1990). Modality specific accounts suggest that a match between the task stimulus and the startle probe modalities will result in facilitated startle, whereas a mismatch will result in attenuated startle. The modality specificity of attentional modulation may occur through the enhancement and inhibition of sensory pathways. The task stimulus may enhance attention to a specific modality and at the same time inhibit stimulus input from other modalities (Silverstein *et al.* 1981, Putnam 1990). Startle eyeblinks are thus facilitated when they are elicited via the enhanced sensory pathway, whereas they are attenuated when elicited via the inhibited sensory pathway. This conceptualisation would suggest that if a visual probe were used to elicit startle during a continuous visual task, startle eyeblink would be facilitated relative to a no-task baseline condition.

The possibility that startle eyeblink may be sensitive to the attentional demands associated with different sensory modalities could be important for workload assessment in specific contexts. As outlined in Wickens (1987) multiple resource model, there may be different attentional resources devoted to specific types of cognitive processes. Wickens (1987) proposed multiple resources along three dimensions of (a) stages of processing, (b) processing codes, and (c) input/output modalities. For the latter, it was suggested that the processing of visual and auditory input require different pools of resources. Wickens (1987) model suggests that it is important to decompose workload demands according to the input modality. If, for instance, a workload assessment finds that the visual workload demands of a system are excessive, the visual interface of the system may need to be redesigned.

Additional research is required to determine if startle eyeblink modulation may prove useful in such an assessment. It is not known if modality specific effects will be observed in combinations of startle probe/primary task modalities other than that examined here. In addition, it is not known if modality specific effects will be observed in tasks that require input from both the visual and auditory modalities. An experiment that varies visual modality workload demands while the auditory modality workload demand is held constant may be the first step in examining this issue. If an auditory startle probe is used, the findings from such an experiment would be expected to be similar to that observed in the present research; attenuation of startle eyeblink as the visual workload demands increase.

A concern with any workload metric is that its application will interfere with task performance or with measurements obtained by other workload measures. This applies particularly for the startle probe methodology as it involves presentation of an eyeblink-eliciting stimulus. This stimulus must be sufficiently intense and abrupt to reliably elicit the eyeblink reflex. However, those characteristics that enhance its startle-eliciting function may also produce interference during the task. The present study examined this issue by comparing conditions that did and did not contain a startle probe stimulus. The pre-task and post-task baseline trials provided an assessment of the influence of the startle probes on the other workload measures independent of the tasks. Only heart period variability as assessed by spectral power analysis was influenced by the presentations of the startle probe. Power in the low frequency component during the pre-task baseline was lower when the startle probe was presented. In addition, power in the high frequency component across the combined baseline and task trials was lower when the startle probe was presented. These findings suggest that the startle probe presentations will decrease heart rate variability as assessed by spectral analysis. It may be that the elicitation of the startle response causes a suppression of the cardiovascular control system and hence reduces the relationship between blood pressure

regulation and respiratory influences on heart rate. Power in the low and high frequency regions respectively are thus reduced. Alternatively, the startle response may have induced temporary changes in respiratory activity and these changes were reflected in the results due to the relationship between respiratory activity and heart rate variability (Stark *et al.* 2000). The influence of the startle response on respiratory activity could not be assessed in the present experiment because respiration was not recorded. Future research should include this measure to provide a closer examination of the relationship between startle eyeblinks, heart period variability, and respiratory activity. Notwithstanding these possibilities, the differences in the baseline trials should be interpreted with caution. This is because comparisons between baseline trials that did and did not contain the startle probe are confounded by order of presentation, as all participants received the no startle condition before the startle condition.

Comparisons between task conditions that did and did not contain the startle probe provided an indication of the intrusiveness of the startle probe presentations on task performance and workload assessment. Task performance, as assessed by tracking performance alone or tracking in combination with the gauge-monitoring task, was unaffected by the presentations of the startle probe. The presentations of the startle probe also had limited effects on the physiological and subjective workload measures. During the task trials, presentations of the startle probe did not interfere with the sensitivity of heart period and heart period variability to the mental workload demands in each condition. Endogenous eyeblink rate was elevated when the startle probe was presented. However, this increase did not interact with the workload demands of the tasks. It is interesting to note that the increase in endogenous eyeblink rate that was found was approximately two blinks per min. This is precisely the same number of reflexive eyeblinks elicited by the startle probe (i.e. the probe density was one per 30 s). Only the subjective measure of workload interacted

with the presence of the startle probe. The subjective ratings indicated that the tracking task imposed less workload demands when there were presentations of the startle probe than when the startle probe was not presented. This finding is contrary to expectations. It may be that presentation of the startle probe reduced subjective workload demands because it helped to maintain an active attentional set during the relatively monotonous tracking task. During tracking task trials in which the startle probe was not presented, participants may have found it difficult to maintain their attention. This interpretation is consistent with the finding that the difference was obtained during the last trial block and not during the first trial block or during the more difficult multiple-task condition. However, further investigation is warranted to ascertain the reliability of the effect. Further research is also required to assess the intrusiveness of the startle probe during different types of tasks. It may be that the startle probe may intrude on performance during tasks that require finer motor control or higher levels of sustained attention.

The intrusiveness of the startle probe was assessed in the present study only when startle was elicited by a noise burst. The startle eyeblink reflex may be elicited by stimuli presented in other sensory modalities, including flashes of light, a tap to the forehead, puff of air to face near the eye, or electrical stimulation of the trigeminal nerve (Berg and Balaban 1999). The different methods of startle elicitation may produce different levels of overall interference. The nature of the interference may also depend on the task the operator is to perform. For instance, the present task was primarily visual and so it may be expected that startle eyeblinks elicited by a flash of light will produce more interference than an acoustic startle probe. The most innocuous startle probe may be the tap to the forehead (often referred to as the glabella reflex). This method has been employed in a wide range of sensitive participants such as 37 week-old infants (Anday *et al.* 1991) and it may prove to be the least likely to produce interference. However, this method, along with all other methods, will

elicit blinks at times not under the control of the participant. The resulting disruption of visual information from the involuntary eyeblink will always be present regardless of which eyeblink eliciting stimulus is used. The development of startle eyeblink as a workload metric would benefit from research on the relative advantages and disadvantages of the eyeblink eliciting methods, both in terms of overall intrusiveness and in the applicability to specific task situations.

A second important issue examined in the present experiment was habituation of the startle eyeblink. The present experiment found reliable habituation effects, although the presence of habituation differed between the latency and magnitude measures of the startle eyeblink. Startle magnitude, but not startle latency, was attenuated during the post-test baseline relative to the pre-test baseline. Habituation during the task trials was observed in both startle latency and magnitude, although an interaction between the task conditions and trial block was observed only for startle magnitude. The latter interaction was due to startle habituating during the single-task condition, but not during the multiple-task condition. Valls-Sole *et al.* (1997) reported a study in which the habituation rate of the startle reflex was significantly reduced in a condition that required participants to prepare to execute a reaction time task relative to conditions in which the participant was at rest in a quiet environment, at rest in a busy environment, and focussing attention on an impending visual stimulus. The authors suggested that habituation rate may be reduced during the preparation for a motor task because of a cortical inhibitory process that blocks stimulation for nonexpected sensory afferents. In addition, the enhancement of the motor pathways may also increase startle reactivity, and hence reduce habituation, if the motor pathways have some overlap with those involved in the startle circuit. A similar explanation may apply for the differences in habituation rates between the two task conditions in the present experiment. That is, the increased motor demands required in the multiple-task condition relative to the single-task

condition may have interfered with the development of habituation for startle magnitude. If the preparation and/or execution of a motor task is important for reduced habituation, it would be expected that habituation of the startle eyeblink would be reduced in continuous tasks that require excessive manual activity (e.g. aircraft control) relative to tasks that require little manual activity (e.g. system monitoring).

The differences in habituation between startle latency and magnitude in the baseline trials are intriguing. Differences in habituation between latency and magnitude have also been observed in research on selective attention (e.g. Silverstein *et al.* 1981) and sensory gating (e.g. Lipp and Krinitzky 1998). It may be that startle latency is less sensitive to habituation effects than is startle amplitude. If this were the case, it would suggest that startle latency might be a preferable measure of workload demands than would startle magnitude when used with some types of tasks. These types of tasks may include those that necessitate a large number of startle probe presentations in order to assess mental workload demands across time or different aspects of the task (e.g. during different flight segments in aircraft control). Nevertheless, the present experiment suggests that startle magnitude will still provide a reliable index of workload demands during these conditions. This is because significant differences between workload conditions across trial blocks were still found in startle amplitude, despite the observed habituation.

The goal of psychophysiological applications in the assessment of mental workload is to develop measures with well known properties that can be applied in specific situations. This goal has come about from the complex nature of the mental workload construct and the acceptance that there is no golden yardstick of mental workload. The present research has provided preliminary findings which suggest that startle eyeblink modulation may provide a valuable addition to currently used workload metrics. Future research may help to elucidate the relative advantages and disadvantages of this measure in particular situations. Two

potential disadvantages investigated in the present research, intrusiveness and habituation, were shown to be negligible or non-existent. They appear to be outweighed by the advantages such as good temporal resolution due to the short latency of the reflex, minimal compliance or attention required from the participant, and the possibility that it may be sensitive to mental workload in different sensory modalities.

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Footnote

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Table 1.

Means for endogenous eyeblink rate, heart period, and heart period variability measures during the baseline and task trials as a function of the presence or absence of the startle probe (standard deviations are in parenthesis).

Dependent variable	Pre-task baseline		Single-task condition		Multiple-task condition		Post-task baseline	
	No startle probe	With startle probe	No startle probe	With startle probe	No startle probe	With startle probe	No startle probe	With startle probe
Endogenous eyeblink rate (per min)	11.38	12.34	6.40	8.27	4.46	5.78	14.74	14.12
	(6.12)	(8.60)	(4.74)	(5.45)	(3.84)	(3.04)	(7.64)	(8.76)
Heart period (ms)	868.99	886.85	863.70	863.72	849.44	848.24	880.68	882.72
	(149.65)	(163.94)	(155.88)	(157.40)	(149.73)	(149.73)	(152.42)	(157.24)
Very low frequency component of heart period (log ms rms ²)	4.80	4.78	4.60	4.69	4.45	4.54	5.04	4.99
	(0.22)	(0.36)	(0.21)	(0.25)	(0.30)	(0.32)	(0.31)	(0.37)
Low frequency component of heart period (log ms rms ²)	4.89	4.69	4.57	4.60	4.43	4.46	4.89	4.90
	(0.30)	(0.27)	(0.25)	(0.24)	(0.31)	(0.28)	(0.23)	(0.21)
High frequency component of heart period (log ms rms ²)	4.72	4.72	4.54	4.54	4.39	4.38	4.75	4.67
	(0.41)	(0.37)	(0.41)	(0.38)	(0.44)	(0.42)	(0.29)	(0.32)

Table 2.

Mean subjective workload ratings during the task trials as a function of the presence or absence of the startle probe and trial block (standard deviations are in parentheses).

Trial block	Single-task condition		Multiple-task condition	
	No startle probe	With startle probe	No startle probe	With startle probe
1	2.35 (0.84)	2.64 (1.08)	4.14 (1.51)	4.43 (1.69)
3	2.93 (1.59)	2.36 (0.93)	4.14 (1.79)	4.57 (1.99)

Table 3.

Tracking task and composite task Z-scores as a function of task condition and the presence or absence of the startle probe (standard deviations are in parenthesis).

Dependent variable	Single-task condition		Multiple-task condition	
	No startle probe	With startle probe	No startle probe	With startle probe
Tracking task score	3.98 (0.22)	3.99 (0.27)	5.01 (0.55)	4.97 (0.74)
Composite task Z-score ^a	-	-	2.11 (0.35)	2.09 (0.32)

^aNo composite task Z-score could be computed for the single-task conditions.

Figure captions

Figure 1. Typical electrode placement and the resulting raw electromyographic (EMG) signal following the presentation of a startle eliciting acoustic probe stimulus that is characteristic of the startle eyeblink reflex.

Figure 2. The visual display that the participant interacted with during the single-task and multiple-task conditions.

Figure 3. Mean startle eyeblink latency (top panel) and magnitude (bottom panel) during the pre-task and post-task baseline conditions and the single-task and multiple-task conditions in each trial block.