Expiratory Threshold Loading and Attentional Performance

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INTRODUCTION: While there are numerous factors that may affect pilot attentional performance, we hypothesize that an increased expiratory work of breathing experienced by fighter pilots may impose a "distraction stimulus" by creating an increased expiratory effort sensation. Therefore, the purpose of this study was to determine the extent to which increasing expiratory pressure time product or expiratory effort sensation impacts attentional performance.

METHODS: Data was collected on 10 healthy participants (age: 29 ± 6 yr). Participants completed six repetitions of a modified Masked Conjunctive Continuous Performance Task protocol while breathing against four different expiratory threshold loads. Repeated measures analysis of variances and generalized additive mixed effects models were used to investigate the effects of expiratory threshold load conditions on expiratory pressure time product, expiratory effort sensation, and the influence of altered end tidal gases on Masked Conjunctive Continuous Performance Task scores.

RESULTS: The overall median hit reaction times were significantly longer as the expiratory threshold loads increased. Specific shape-conjunctive and non-conjunctive median hit reaction times were longer with increased expiratory effort sensation. Additionally, increased expiratory effort sensation did not significantly change commission error rates, but did significantly increase omission error rates.

DISCUSSION: The findings of our work suggest that both progressively greater expiratory threshold loads during spontaneous breathing and expiratory effort sensation may impair subjects' attentional performance due to longer reaction times and increased stimuli recognition error rates.

KEYWORDS: work of breathing, expiratory loading, attentional performance, reaction time, pilot health.

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The U.S. Air Force fleet of high-performance aircraft are capable of imposing supra-physiological perturbations on pilots. Despite the superlative features of these high-performance aircraft, it has become apparent over the past decade that they are not designed for pilot optimization such that flying these aircraft have posed a number of serious concerns for pilot health and safety. In fact, there was a fleet wide stand-down in May 2011 as a result of increased physiological events.[1] As a result, several task forces were assembled to further elucidate the physiology associated with piloting high-performance aircraft in an effort to optimize pilot performance. To this end, the Restrictive Breathing Working Group demonstrated that breathing on the F-22 Life Support System resulted in an excessively high mechanical work of breathing.[1] Additionally, a recent technical report published by the National Aeronautics and Space Administration Pilot Breathing Assessment suggests the life support systems in high-performance aircraft may play a role in work of breathing (W_b). In fact, this assessment demonstrated pressure-flow phase shifts wherein there is a lag between positive mask pressure generation and expiratory flow (i.e., slow regulator response), indicating increased expiratory pressure owing to pilots' statements of difficulty exhaling.[2] The Pilot Breathing Assessment considered

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these findings highly concerning as airflow supplied by the life support system is variable, inconsistent, and is not well designed to synchronize with spontaneous pilot breathing demands and, as such, pilots often reported difficulty during exhalations.[2] These findings suggest reducing pilot W_b may protect against physiological events in high-performance aircraft.

In addition to the high W_b imposed by high-performance aircraft, working in operational aerospace environments may impose additional W_b demands, including high gravitational forces (i.e., G forces) exerted on the thorax, decreasing chest wall compliance,[3,4] and increasing the elastic W_b (for review see Glaister[5]). During a high-G exposure, pilots are instructed to perform anti-G straining maneuvers to protect against loss of consciousness—maneuvers that may also incur a significant respiratory load.[6] Other pilot-specific respiratory loads that may influence expiratory W_b include those caused by the additional respiratory pressures that a pilot must develop to generate airflow through the pilot's mask and/or the Onboard Oxygen Generation System (e.g., safety pressure and positive pressure breathing for high-G maneuvers and/or altitude), a slow regulator response, poorly seated or sticking expiratory and inspiratory valves, mask compensation tubes, and/or equipment malfunctions. These factors suggest that breathing during high-performance flight operations is an energetically demanding task for the expiratory muscles.

At rest, the act of breathing is an unconscious experience wherein the muscular effort of breathing is rarely perceived. However, when the mechanical load imposed on the respiratory muscles is increased, the sensation of breathing effort may also increase to a point of engendering negative affective sensations, including increased breathing effort/discomfort, air-hunger, unsatisfied inspiration, or chest tightness.[7–9] As such, it has been proposed that elevated respiratory muscle effort may occupy a portion of the conscious experience in that cognitive resources must be dedicated to "paying attention" to these negative sensations.[10] Consequently, it follows that an increased perception of respiratory muscle effort may directly impact attentional performance of the jet fighter pilot. Indeed, previous work by our group demonstrated an increased perception of inspiratory effort sensation negatively impacts attentional performance.[11] However, as stated above, there also exists a range of expiratory loads imposed on pilots during flight. Therefore, the primary objective of this work was to evaluate the impact of increasing the expiratory W_b on attentional performance in healthy adults. We hypothesized that under circumstances of increased expiratory muscle effort, such as that incurred during expiratory threshold loading, the augmented perception of expiratory muscle effort would compete for available cognitive resources, impairing subjects' attentional performance.

METHODS

Subjects

The present study conformed to the principles outlined in the Declaration of Helsinki and was approved by the Mayo Clinic Internal Review Board. Each subject provided written informed consent prior to participating. Recruited for this study were 12 healthy male subjects (age: 29 ± 6 yr). Subjects had no known history of cardiac, pulmonary, and/or metabolic disease, and no reported mental or psychological disorders of attention. Two subjects were removed from the analysis due to technical difficulties during data collection ($N = 10$).

Procedure

Subjects reported to the laboratory on two separate occasions. During the first visit, pulmonary function testing was performed and subjects were familiarized with the Masked Conjunctive Continuous Performance Task (MCCPT), a psychometric tool used to assess attentional performance through measuring reaction time and error rates.[12] To accurately obtain reaction times (RT), we developed a novel microcontroller-based device. This device provided RT values with a sub-millisecond accuracy. The original version of the MCCPT developed by Shalev et al.[12] takes approximately 20 min to complete. Given our intention was to examine attentional performance across various heavy expiratory loads, it was not reasonable to apply a given expiratory threshold load for such an extended duration of time. Therefore, we modified the original MCCPT by dividing the protocol into 6 trials lasting 150 s each (~40 stimulus presentations per trial). This modification allowed us to apply a given threshold load for a relatively brief duration of time and, through the six repetitions, we were able to accumulate the necessary number of stimulus responses to compute the RT and error rate scores as per the original version of the MCCPT.

The study flow for Visit 2 is as follows. Subjects breathed using a two-way nonrebreathing valve to separate the inspiratory and expiratory circuits. Inspiratory and expiratory flows were measured separately using heated pneumotachographs (3813 series, Hans Rudolph, Shawnee, KS, United States). A humidifier was arranged in series with the inspiratory limb of the circuit. A computer-controlled adjustable poppet valve was inserted between the expiratory port of the two-way nonrebreathing valve and the humidifier. The subject was instructed to complete 24 trials of the MCCPT protocol (40 visual stimuli per trial). During each trial of this MCCPT protocol, one of four loads were randomly added to the expiratory circuit in such a way that the peak expiratory mouth pressure achieved either <5%, ~10%, ~20%, or ~40% of the recorded baseline maximal expiratory pressures (MEPs), denoted herein as loads 1 (control), 2, 3, and 4. These loads were randomly imposed until each load was presented for a total of 6 repetitions (i.e., 24 total trials). Immediately after each trial was completed, the subject was asked to rate their perceived expiratory muscle effort required to breathe against the load on a modified 10-point category ratio scale.[13] Subjects wore noise-cancelling headphones to reduce environmental distractions during the MCCPT. Approximately 2 min of rest was given between each trial. After every six trials the subject was given an ~10-min break where they were free to move and walk around. However, during each six-trial run, subjects were asked to remain on the mouthpiece. Maximal expiratory pressures were obtained between each block of six trials to assess whether expiratory muscle fatigue was evident. Expiratory pressure testing was conducted according to American Thoracic Society and the European Respiratory Society recommendations.[14]

So as not to further distract the subject during MCCPT trials, we did not provide any visual or auditory feedback on breathing pattern and respiratory muscle effort. No feedback on breathing pattern or pressure-development was given to the subjects and, as such, the ventilatory responses during the MCCPT trials and loading conditions were spontaneous. As such, subjects were not obliged to maintain a specific breathing pattern. The four loads were determined on a subject-by-subject basis before data collection began. The investigator varied the load imposed until the peak mouth pressure swing was ~10% of the recorded baseline MEP – this condition was set as load 2. Loads 3 and 4 were determined as peak expiratory mouth pressure swings of ~20% and ~40% of baseline MEP, respectively. Load 1 (i.e., control condition) was set at minimal load with the poppet valve fully opened. Importantly, each load (1 through 4) was determined while the subject was practicing the MCCPT protocol. Because subjects were spontaneously breathing during the loaded trials, the peak mouth pressure swings for a given "intended" load were liable to change slightly over the course of the 24 experimental trials. Hence, it was sometimes necessary to adjust the resistance at a given load to bring the peak expiratory mouth pressure swing back into the desired range. Although a rare occurrence, if any adjustments were necessary, they were performed between and not during trials.

The MCCPT was used to assess continuous attentional performance. In short, a colored "mask" comprised of four superimposed shapes of different color (circle, square, triangle, and hexagon) was presented on screen. To avoid habituation effects, two mask images of differing outline thickness were alternated every 10 – 20 ms. The mask was removed to reveal either the target (i.e., red circle) or a distractor (i.e., any other combination of shape and color). Additionally, the interstimulus interval was randomly jittered between 2000 and 5000 ms. The MCCPT was chosen because we felt that this tool best measured attentional performance using the subjects' RT as we progressively increased expiratory threshold loads. Additionally, we reasoned that the MCCPT more closely aligns with a high-performance aircraft pilot's need to discriminate visual objects during flight operations; i.e., they are required to expeditiously interpret shapes and colors and make appropriate decisions based on these interpretations.

The principal measurement used in the computation of the attentional performance scores of the MCCPT is subjects' RT in response to the stimulus presentation (i.e., target or distractor). The precise measurement of RT is therefore dependent on the degree of precision with which both stimulus presentation and the responding mechanical keypress can be recorded. To this end, our custom-built microcontroller device measured the onset of stimulus presentation via a light sensor attached to the LCD computer display. The mechanical keypress was readily detected as a switching state from high to low on a digital input port of the microcontroller. The time elapsed between these two events was measured via an interrupt-driven routine on the microcontroller that was able to provide elapsed durations with sub-millisecond precision. The microcontroller device communicated with a host PC via USB, such that trial correctness could be matched with the RT measured by the microcontroller device. Each stimulus presentation was coded into one of the following two categories, depending on the shape and color of the stimuli:

- Conjunctive = Stimuli with the same shape or color to the target.
  - Color conjunctive = stimuli with the same color as the target.
  - Shape conjunctive = stimuli with the same shape as the target.
- Nonconjunctive = stimuli with a different shape and/or color to the target.

Color conjunctive and shape conjunctive stimuli will be henceforth referred to as "color" and "shape", respectively.

Only correct responses were used in the calculation of hit RT values. RT values were excluded from analysis if the observed value was <200 ms or ≥1000 ms.[11] This filtering was done as RTs <200 ms were considered either a "false start" or a late response to the previous stimuli and RTs ≥1000 ms were defined as a nonresponse. It is important to note that no responses were outside of these RT limits (e.g., the fastest observed RT was 271 ms). The resulting distributions of RT values for each subject were typically nonnormal and, as such, median RTs for the above conditions were computed for each loading condition, separately. Additional parameters computed were error types (i.e., commission and omission) based upon the ability to discriminate the target from the distractor (d′). Two error types are possible: commissions and omissions, and the criteria (β) which provides a measure of the balance between error types.

$$d' = z(\text{hit rate}) - z(\text{false alarm rate}) \qquad \text{Eq. 1}$$

$$\beta = \text{covariance/variance} \qquad \text{Eq. 2}$$

Omission errors refer to a subject not responding to a stimulus the subjects were supposed to (e.g., not responding to a red triangle), whereas a commission error refers to a subject responding to a stimulus the subject was not supposed to (i.e., responding to a red circle). For β, a positive value means a higher tendency toward omission errors and vice versa (when β value is zero, there is no bias toward any error type).

Mouth pressure was sampled via a lateral port located in the mouthpiece. Inspiratory and expiratory flows were measured separately using heated pneumotachographs (3813 series, Hans Rudolph). Respiratory muscle effort was expressed as the pressure-time product (PTP), which was quantified as the product of the average expiratory mouth pressure and the duration of expiration for expiratory phases.

The partial pressures of oxygen and carbon dioxide ($P_{ET}O_2$ and $P_{ET}CO_2$, respectively) were measured via a rapid-response O_2/CO_2 analyzer (GA-200B, iWorx, Dover, NH, United States) from a sample line placed in the expiratory limb of the experimental breathing circuit. Pulse oxygenation was measured via the fingertip of the nondominant hand (Radical 7, Masimo, Irvine, CA, United States). Heart rate and rhythm were recorded using a single-channel bio-amplifier module (FE132, ADInstruments, Sydney, New South Wales, Australia).

Statistical Analysis

The measured and computed variables obtained during the six repetitions of each load were averaged to provide a single value per load, per subject. Repeated measures analyses of variance were used to determine the effect of increasing expiratory threshold load (1, 2, 3, and 4) on respiratory mechanics, breathing pattern, end-tidal gases, and MCCPT performance. Additionally, the resulting distributions of RT values for each subject were typically nonnormal and, as such, median RTs for the above conditions were computed for each loading condition, separately.

Generalized additive mixed effects models (GAMMs) were used to determine the impact of respiratory mechanics, respiratory effort sensation, $P_{ET}CO_2$, and $P_{ET}O_2$ on MCCPT scores. The parameter of respiratory mechanics that was chosen as a covariate in these GAMM models was the expiratory PTP generated in response to each loading condition. $P_{ET}CO_2$ and $P_{ET}O_2$ were calculated as a change from baseline to account for the variability in subject resting end-tidal partial pressures. Statistical significance was considered if $P < 0.05$.

The GAMM models used in this study were selected through the examination of multiple competing models. Competing distributional families were compared using the Akaike information criterion to determine which family was most appropriate. Through these comparisons, we determined that a log-link Gamma distribution most closely fit the data for the reaction time models, and a beta regression family most closely fit the data for the error rate models. Included in these models were main effects for respiratory effort sensation, expiratory PTP, $P_{ET}CO_2$, and $P_{ET}O_2$. Random intercepts for subject ID and random slopes for respiratory effort sensation, expiratory PTP, $P_{ET}CO_2$, and $P_{ET}O_2$ were also included. It is important to note that while hyper- and hypocapnia have been associated with altered cognitive performance, there are conflicting reports as to their relationship.[15–17] The incidence of altered $P_{ET}CO_2$ and the lack of consensus as to how altered arterial CO_2 may affect cognition were the primary factors in our decision to include $P_{ET}CO_2$ in our GAMM models.

The selection of group-level main effects and interaction terms was determined using a backward selection method based on the Akaike's Information Criteria score.[18] The final GAMM model was fit using the restricted maximal likelihood method, cubic regression penalties for nonlinear smooths, the hyperparameter γ, which was calculated using Bayesian Information Criterion-like parameters [i.e., log(n)/2] to reduce overfitting, and a false discover *P*-value adjustment to reduce false positives.[19,20] An extra penalty was added to each individual term so it could be penalized to zero, thereby allowing terms to be automatically "selected out" from the GAMM when appropriate.

RESULTS

The expiratory PTP (1.36 ± 0.49 vs. 132.67 ± 77.51 $cmH_2O \cdot s^{-1}$ for load 1 vs. load 4) and expiratory effort sensation (0 ± 0 vs. 7.26 ± 1.63 for load 1 vs. load 4) together increased with augmenting expiratory threshold load ($P < 0.001$). There were no signs of significant expiratory muscle fatigue throughout Visit 2, as evidenced by the steady values of MEP following each testing block. Additionally, there was a load-dependent rise in the magnitude of peak expiratory mouth pressure swings (0.94 ± 0.31 vs. 45.67 ± 20.67 cmH_2O for load 1 vs. load 4) ($P < 0.001$). Further, a pattern of increasing mean expiratory mouth pressure was observed with augmenting expiratory loads (0.49 ± 0.18 vs. 24.62 ± 10.36 cmH_2O for load 1 vs. load 4) ($P < 0.001$). We are thus confident that our approach to determining and imposing the four different loads did, in fact, engender separate expiratory PTP measures and evoked unique increases in the expiratory effort sensation.

Our data did demonstrate variability in the breathing pattern response to expiratory threshold loading. However, there was a clear influence of expiratory threshold loading on minute ventilation wherein minute ventilation decreased at the highest expiratory threshold loads (i.e., loads 3 and 4). This decrease in minute ventilation was the result of a decreased breathing frequency rather than tidal volume, wherein breathing frequency during loads 2, 3, and 4 were significantly lower than load 1 ($P < 0.001$). These altered respiratory patterns were accompanied by a progressive increase in $P_{ET}O_2$ with no change from load 3 to 4 and no significant change in $P_{ET}CO_2$.

There were observable changes in MCCPT performance between expiratory threshold loading conditions. Specifically, median hit RT was significantly longer during loads 3 and 4 compared with load 1 (476.9 ± 56.0 ms and 465.6 ± 69.7 ms for loads 3 and 4, respectively, vs. 458.6 ± 97.5 ms for load 1) (**Table I**, **Fig. 1A**; $P < 0.05$). However, there were no differences in the average omission or commission error rates observed between the expiratory loading conditions. Furthermore, there was no difference between loads for median hit RT when presented with shape and nonconjunctive distractor stimuli. There was,

Table I. Median Hit Reaction Times Across Expiratory Threshold Loading Conditions.

CONDITION	MEAN (ms)	SD	*P*-VALUE
1 (No Load)	458.6	97.5	
2 (Light Load)	448.8	53.9	0.56
3 (Moderate Load)	467.9	56.0	**0.030**
4 (Heavy Load)	465.6	69.7	**0.047**

SD: standard deviation. Bolded *P*-values denote a significant difference between the expiratory load and load 1 ($P < 0.05$).

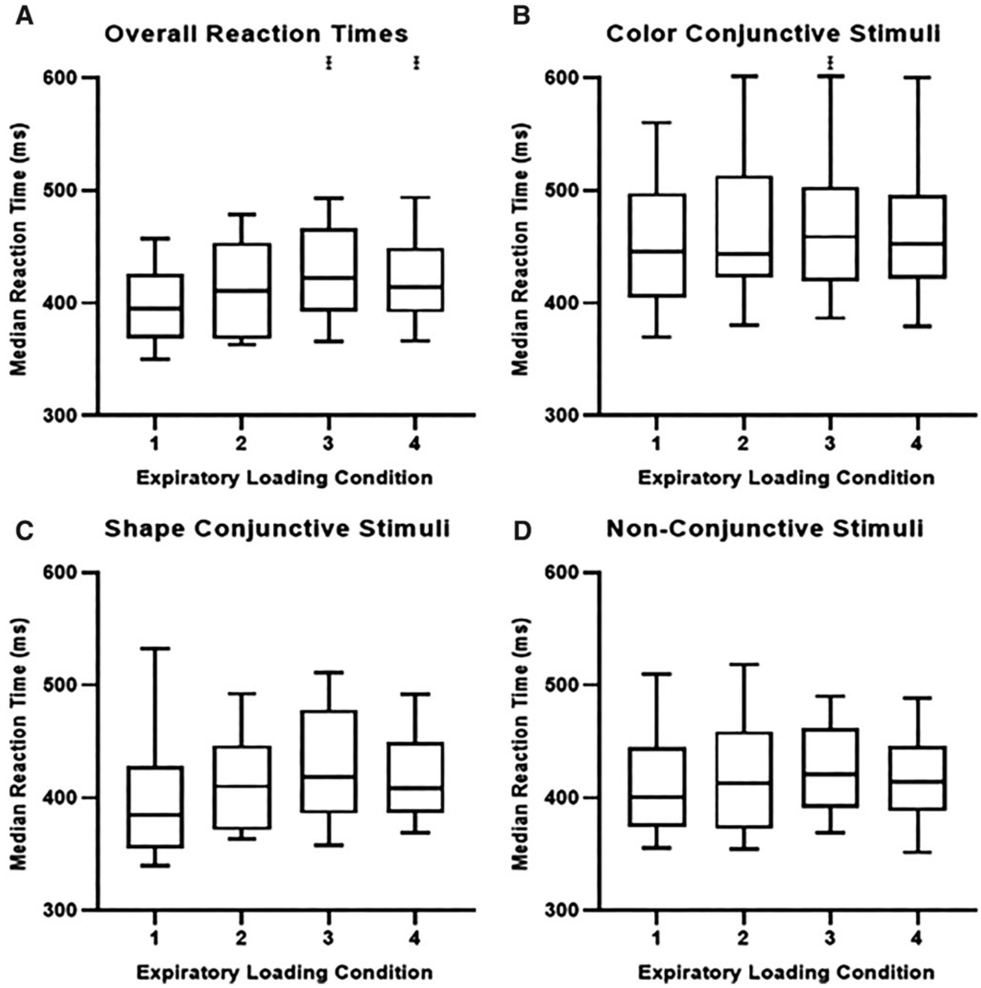

Fig. 1. Median reactions times for different stimuli across inspiratory threshold loading conditions during masked conjunctive continuous performance trials. Values represent means ± SEM. ‡Significant difference from load condition 1, $P < 0.05$.

however, a significant difference in median hit RT between load 1 and load 3 when presented with a color distractor stimulus (441.33 ± 63.61 ms and 514.63 ± 179.20 ms for loads 1 and 3, respectively) ($P = 0.01$) (**Fig. 1B**).

Interestingly, there was no effect of expiratory PTP on overall median hit RT (**Table II**). Additionally, there was no effect of expiratory effort sensation on overall median hit RT (Table II). However, when median hit RTs are stratified by stimuli type, there was an effect of expiratory effort sensation on median hit RT for shape and nonconjunctive stimuli, but not for color stimuli. Specifically, as expiratory effort sensation increased, median hit RT increased as well for both nonconjunctive and shape stimuli (**Fig. 2** and **Fig. 3**, respectively). Similarly, shape stimuli median hit RTs increased when expiratory effort sensation increased until an effort sensation rating of ∼6 (i.e., strong to very strong), after which median hit RTs were maintained as effort sensation further increased (Fig. 3).

We also observed a similar relationship between median hit RT and $P_{ET}CO_2$, wherein there was no main effect of $P_{ET}CO_2$ (Table II) on overall median hit RT, yet there was a main effect of $P_{ET}CO_2$ on shape, color, and nonconjunctive stimuli (**Table III**). Indeed, as $P_{ET}CO_2$ decreased from baseline, median hit RT increased. On the other hand, as $P_{ET}CO_2$ increased from baseline, the median hit RT decreased. These data suggest lower $P_{ET}CO_2$ is associated with higher median hit RTs while higher $P_{ET}CO_2$ is associated with lower median hit RTs.

There was no effect of expiratory threshold loads, expiratory effort sensation, expiratory PTP, or percent change in $P_{ET}CO_2$ nor $P_{ET}O_2$ on total error rates (**Table IV**). However, when total error rates were stratified by error type, we observed a significant effect of percent change in $P_{ET}CO_2$ on commission error rates. Specifically, any deviation in $P_{ET}CO_2$, whether above or below baseline, was associated with a decrease in commission error rates (**Fig. 4**). In addition, omission error rates significantly increased (but commission error rates did not significantly change) with increased expiratory effort sensation.

DISCUSSION

The present work examined the effects of expiratory threshold loads on attentional performance. It is apparent from our data that by imposing progressively larger expiratory threshold loads

Table II. GAMM Results for Overall Median Hit Reaction Time During Expiratory Loaded Trials.

EFFECT	ESTIMATE*	SE	STATISTIC	*P*-VALUE
Main Effect				
Intercept	6.08	0.03	192.1	**<0.001**
s (effort sensation)	1.37	-	3.07	0.49
s (pressure-time product)	0.43	-	5.63	0.63
s ($\Delta P_{ET}CO_2$)	0.62	-	10.22	0.31
s ($\Delta P_{ET}O_2$)	<0.01	-	0.00	0.69
Random Effects		-		
ID	9.64		391.57	**<0.001**
ID: effort sensation	5.68	-	157.17	**<0.05**
ID: pressure-time product	<0.01	-	0.00	**<0.05**
ID: $\Delta P_{ET}CO_2$	<0.01	-	0.00	**<0.05**
ID: $\Delta P_{ET}O_2$	<0.01	-	0.00	**<0.001**

SE: standard error; statistic refers to the *t*-value for the intercept and the *F*-value for the smooth terms and random effects; pressure-time product was measured in $cmH_2O \cdot min^{-1}$; $\Delta P_{ET}CO_2$ and $\Delta P_{ET}O_2$ were measured in mmHg; bolded *P*-values denote a significant influence of the covariate term on overall median hit reaction times ($P < 0.05$). *For all smooth terms [s()] this estimate represents the estimated degrees of freedom of the corresponding smooth.

during spontaneous breathing, median hit RTs were longer. However, through interrogation of nonlinear trends in the data, it appeared that expiratory effort sensation was the primary moderator of longer median hit RTs for shape and nonconjunctive (but not color) stimuli. Stated in other words, the observed differences in median hit RTs were influenced by the participant's perception of breathing effort, independent of the actual load applied.

As such, the most robust finding of the present work was that overall median hit RT was not associated with expiratory effort sensation during expiratory threshold loads per se. However, it appears there is significant individual variability in the subjects' median hit RT responses to expiratory threshold loads. While there was no main effect of expiratory effort sensation on overall median hit RTs, when RTs are stratified by stimuli type, there was a significant effect of expiratory effort sensation on median hit RT for shape and nonconjunctive stimuli. Specifically, as expiratory effort sensation increased, median hit RT increased as well for both shape and nonconjunctive stimuli. Examination of the nonlinear trends suggest median hit RTs may increase by as much as 27 ms and 60 ms for shape and nonconjunctive, respectively, as expiratory effort sensation increases from 0 to 10. While these median hit RT delays may appear trivial, the authors would argue they constitute an operationally relevant impediment in an environment when only tight margins of error can be tolerated.

Interestingly, large expiratory loads (i.e., loads 3 and 4) appear to have little influence on a subject's engagement and, thus, the ability to discriminate between the target and distractor stimuli.[21] Additionally, these data suggest that in response to imposing a high expiratory load, subjects may have adopted altered respiratory patterns of decreased minute ventilation resultant to decreased breathing frequency to avoid the load and minimize respiratory effort sensation, a finding consistent with previous literature.[22,23] However, this respiratory pattern may result in relative hypoventilation, increasing $P_{ET}CO_2$. It is important to note that while hyper- and hypocapnia have been associated with altered cognitive performance, there are conflicting reports as to their relationship (i.e., positive or negative).[15–17] However, in this study, $P_{ET}CO_2$ did not change despite a fall in minute ventilation (V_E). Our data did demonstrate a parabolic relationship between $P_{ET}CO_2$ and commission error rates during expiratory loaded trials. Specifically, any deviation in $P_{ET}CO_2$ from approximate baseline levels is associated with increased commission error rates.

Interestingly, an increase in expiratory effort sensation was associated with a significant increase in omission error rates and a nonsignificant trend for decreased commission error rates. It must be noted that decreased commission error rates

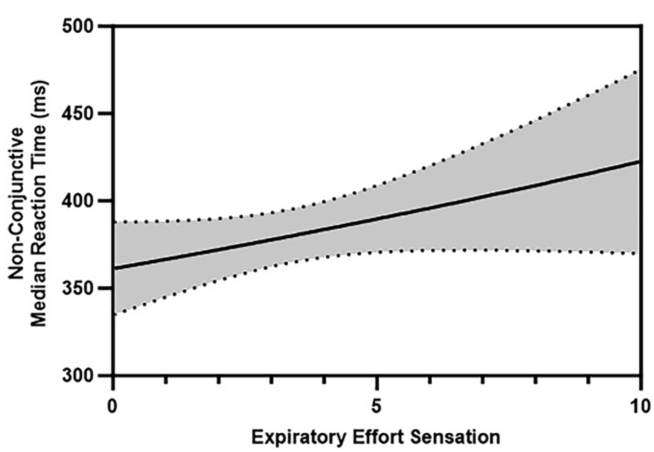

Fig. 2. Predicted smooth in nonconjunctive median reaction time across expiratory effort sensation. The predicted smooth of median reaction time was obtained from GAMM modeling of measures of median reaction time where expiratory effort sensation, expiratory PTP, $\Delta P_{ET}O_2$, and $\Delta P_{ET}CO_2$ were entered into the model as covariates. The predicted smooth curve was produced for median reaction time by setting all other covariates at their means. The dashed curves show the 95% confidence intervals around the prediction.

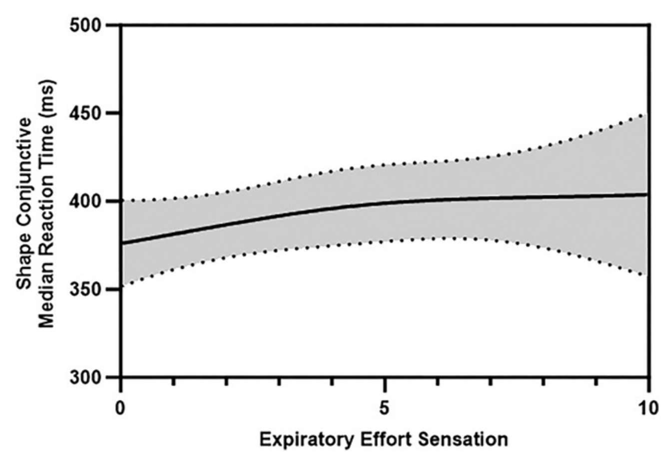

Fig. 3. Predicted smooth in shape conjunctive median reaction time across expiratory effort sensation. The predicted smooth of median reaction time was obtained from GAMM modeling of measures of median reaction time where expiratory effort sensation, expiratory PTP, $\Delta P_{ET}O_2$, and $\Delta P_{ET}CO_2$ were entered into the model as covariates. The predicted smooth curve was produced for median reaction time by setting all other covariates at their means. The dashed curves show the 95% confidence intervals around the prediction.

Table III. GAMM Results for Median Hit Reaction Time for Color, Shape, and Non-Conjunctive Stimuli During Expiratory Loaded Trials.

EFFECT	ESTIMATE*	SE	STATISTIC	*P*-VALUE
Color Conjunctive Stimuli				
Main Effects				
Intercept	6.14	0.03	244.6	**<0.001**
s (effort sensation)	0.23	-	0.12	0.07
s (pressure-time product)	0.01	-	0.00	0.07
s ($\Delta P_{ET}CO_2$)	0.79	-	13.52	**<0.001**
s ($\Delta P_{ET}O_2$)	<0.01	-	0.00	0.07
Random Effects				
ID	8.10	-	162.03	**<0.001**
ID: effort sensation	4.94	-	42.96	**<0.001**
ID: pressure-time product	2.02	-	30.59	**<0.05**
ID: $\Delta P_{ET}CO_2$	<0.01	-	0.00	0.07
ID: $\Delta P_{ET}O_2$	<0.01	-	0.00	0.12
Shape Conjunctive Stimuli				
Main Effects				
Intercept	6.08	0.04	168.4	**<0.001**
s (effort sensation)	1.53	-	1.99	**<0.001**
s (pressure-time product)	<0.01	-	0.00	0.35
s ($\Delta P_{ET}CO_2$)	1.38	-	13.81	**<0.001**
s ($\Delta P_{ET}O_2$)	<0.01	-	0.00	0.35
Random Effects				
ID	9.76	-	94.28	**<0.001**
ID: effort sensation	<0.01	-	0.00	**<0.05**
ID: pressure-time product	<0.01	-	0.00	**<0.05**
ID: $\Delta P_{ET}CO_2$	<0.01	-	0.00	0.16
ID: $\Delta P_{ET}O_2$	<0.01	-	0.00	0.16
Non-Conjunctive Stimuli				
Main Effects				
Intercept	6.07	0.03	197	**<0.001**
s (Effort Sensation)	0.72	-	2.81	**<0.01**
s (pressure-time product)	<0.01	-	0.00	0.41
s ($\Delta P_{ET}CO_2$)	0.73	-	10.99	**<0.01**
s ($\Delta P_{ET}O_2$)	<0.01	-	0.00	0.75
Random Effects				
ID	9.48	-	195.77	**<0.001**
ID: effort sensation	<0.01	-	52.51	**<0.001**
ID: pressure-time product	<0.01	-	0.00	**<0.05**
ID: $\Delta P_{ET}CO_2$	<0.01	-	0.00	**<0.01**
ID: $\Delta P_{ET}O_2$	<0.01	-	0.00	**<0.05**

SE: standard error; statistic refers to the *t*-value for the intercept and the *F*-value for the smooth terms and random effects; pressure-time product was measured in $cmH_2O \cdot min^{-1}$; $\Delta P_{ET}CO_2$ and $\Delta P_{ET}O_2$ were measured in mmHg; bolded *P*-values denote a significant influence of the covariate term on overall median hit reaction times ($P < 0.05$). *For all smooth terms [s()] this estimate represents the estimated degrees of freedom of the corresponding smooth.

and increased omission error rates were both products of nonresponses, in that not responding to the target stimuli would increase omission errors and not responding to the distractor stimuli (i.e., red circle) would improve commission errors. As such, these results may suggest a global reduction in attentional performance.

These data support our hypothesis that under circumstances of increased expiratory threshold loading, the augmented perception of respiratory muscle effort would compete

Table IV. GAMM Results for Total Error Rates During Expiratory Loaded Trials.

EFFECT	ESTIMATE*	SE	STATISTIC	*P*-VALUE
Main Effects				
Intercept	– 0.81	0.12	– 6.69	**<0.001**
s (effort-sensation)	<0.01	-	0.00	0.49
s (pressure-time product)	<0.01	-	0.00	0.63
s ($\Delta P_{ET}CO_2$)	<0.01	-	0.00	0.31
s ($\Delta P_{ET}O_2$)	<0.01	-	0.00	0.69
Random Effects		-		
ID	9.11		1340.2	**<0.001**
ID: effort-sensation	5.13	-	641.7	**<0.001**
ID: pressure-time product	<0.01	-	0.00	**<0.05**
ID: $\Delta P_{ET}CO_2$	<0.01	-	0.00	**<0.05**
ID: $\Delta P_{ET}O_2$	<0.01	-	0.00	**<0.05**

SE: standard error; statistic refers to the *t*-value for the intercept and the *F*-value for the smooth terms and random effects; pressure-time product was measured in $cmH_2O \cdot min^{-1}$; $\Delta P_{ET}CO_2$ and $\Delta P_{ET}O_2$ were measured in mmHg; bolded *P*-values denote a significant influence of the covariate term on overall median hit reaction times ($P < 0.05$). *For all smooth terms [s()] this estimate represents the estimated degrees of freedom of the corresponding smooth.

for available cognitive resources, impairing subjects' attentional performance. Impaired attentional performance associated with increased expiratory threshold loads appeared to negatively impact discriminating shape and nonconjunctive stimuli. Decreased attentional performance associated with increased expiratory effort sensation appeared to significantly increase omission error rates, and also led to longer specific stimuli median hit RTs. Thus, we believe the increased expiratory threshold loads and expiratory effort sensation created a "distraction" stimulus that may have negatively impacted attentional performance.

Longer reaction times and increased visual object recognition errors would be detrimental to a fighter pilot while flying in time compressed and high physical effort operations.

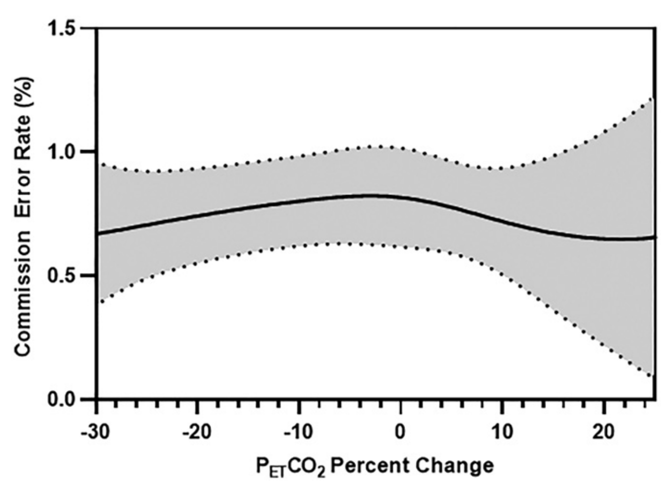

Fig. 4. Predicted smooth in commission error rates for percent change $P_{ET}CO_2$ from baseline. The predicted smooth of commission error rates was obtained from GAMM modeling of measures of commission error rates where percent change in $P_{ET}CO_2$, expiratory effort sensation, expiratory PTP, and percent change in $P_{ET}O_2$ and $P_{ET}CO_2$ were entered into the model as covariates. The predicted smooth curve was produced for commission error rates by setting all other covariates at their means (expiratory effort sensation = 3.79; expiratory PTP = 72.73 $cmH_2O \cdot s^{-1}$; $\Delta P_{ET}O_2$ = 11.39%). The dashed curves show the 95% confidence intervals around the prediction.

Therefore, future research might focus on systems that could minimize expiratory threshold loads, expiratory effort sensation, and variations from baseline for end-tidal gas concentrations during flight operations. The data from this paper suggests that these goals may support shorter pilot reaction times and lower visual recognition errors during high performance flight operations.

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