Cognitive interference of respiratory *versus* limb muscle dual tasking in healthy adults

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Respiratory muscle dual tasking results in greater prefrontal cortex activity, cognitive interference and perception of effort than limb muscle dual tasking, despite pedalling eliciting a heightened cardiovascular response. https://bit.ly/3wDYPQc

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Abstract

Background Inspiratory threshold loading (ITL) and associated dyspnoea have been shown to interfere with cognition during cognitive–motor dual tasking. However, ITL has not been compared with another rhythmic muscle activity, such as lower limb pedalling. While ITL has been shown to interfere with cognition, the mechanism of the prefrontal cortex (PFC) during ITL or other rhythmical muscle dual tasking, has not been elucidated. Given the cognitive interference that arises during ITL, we hypothesise that ITL cognitive–motor dual tasking will result in greater cognitive decrements and increased PFC activity compared with the pedalling cognitive–motor dual task.

Methods 30 healthy participants (16 females; median age 23 (interquartile range 23–24) years) were recruited. They performed five 3-min tasks in a single visit in a random order: single tasks were ITL, pedalling and Stroop task and dual tasks were ITL–Stroop and pedalling–Stroop. Participant's PFC activity was assessed bilaterally using functional near-infrared spectroscopy throughout each task. Single- and dual-task cognitive performance was evaluated by measuring Stroop task reaction time and accuracy. Dyspnoea and rating of perceived exertion were evaluated at the end of each task.

Results ITL–Stroop resulted in greater impairments in reaction time ($p<0.001$), accuracy ($p<0.01$) and increased medial/dorsolateral PFC activity ($p\leqslant0.006$) than pedalling–Stroop. ITL–Stroop elicited greater Borg dyspnoea and rating of perceived exertion than pedalling–Stroop ($p<0.001$), despite pedalling–Stroop having a greater heart rate response ($p<0.001$).

Conclusion The heightened cognitive decrements, perceptual response and PFC activity suggest that inspiratory muscle loading and its accompanied dyspnoea results in greater cognitive interference than rhythmic pedalling.

Introduction

Although many daily activities demand cognitive processing combined with physical exertion, clinical exercise prescription to older adults and those with respiratory disease is often based on peripheral outcomes of exercise capacity (*e.g.* heart rate (HR)) [1, 2]. Increased ventilatory demands in these conditions require greater respiratory muscle recruitment. Importantly, inspiratory threshold loading (ITL) with associated dyspnoea can activate motor, affective and cognitive networks [3]. Consequently, dyspnoea may not only interfere with movement due to its aversive nature, but also through its cognitive load taxing relevant networks [3].

The proposed relationship between dyspnoea and cognition has been elucidated by studies demonstrating that ITL-induced dyspnoea in healthy adults impedes various cognitive processes in dual-task scenarios (the concurrent performance of two tasks) [4–6]. It has been postulated that the shared cortical networks subserving dyspnoea and other cognitive processes may become limited when both tasks are performed concurrently [4–6]. Aside from an exploratory study of unilateral pedal pushing [7], dyspnoea has not been contrasted with other rhythmic motor tasks. Investigating the role of inspiratory muscle loading *versus* rhythmic leg exercise during cognitive–motor dual tasking could help delineate their cardiovascular demands, their perceptual response and impact on cognition. This is clinically important in the context of heightened respiratory perception, such as during or following respiratory exacerbations, chronic refractory dyspnoea and the subsequent impact dyspnoea or limb perception has on these patient's activities of daily living (ADLs).

Factors sought to influence perception of effort during exercise have traditionally focused on peripheral afferent feedback [8]. Scales such as the Borg rating of perceived exertion (RPE) have been commonly utilised to tailor exercise prescriptions, especially given its estimation of HR [9]. However, this proposed link between perception of effort and afferent input from skeletal muscle and the cardiorespiratory system has been challenged in recent years [8]. Rather, corollary discharge theory has postulated that perception of effort is induced by output from the motor-related cortical regions to the somatosensory cortex [8, 10]. Taken together, both afferent input and corollary discharges are hypothesised to influence effort perception [11]. Moreover, other upstream regions such as the prefrontal cortex (PFC) [11, 12] are also implicated in effort perception. Consideration of the PFC is particularly significant for cognitive–motor dual tasking, given the PFCs role in cognition and higher-order processing.

Functional near-infrared spectroscopy (fNIRS) is well suited for investigating PFC activity during cognitive and physical tasks, given its unobtrusive application, relative resistance to motion artefacts and portability [13]. It has been previously utilised during ITL [14] and pedalling. Continuous-wave fNIRS measures absorption of near-infrared light to evaluate changes of oxygenated haemoglobin (ΔO_2Hb) that results from the increased vascular response to augmented neuronal activity. Hence, the neurovascular coupling associated with increases in neural activity results in an increase in ΔO_2Hb, a surrogate measure of neural activity [15].

Previously, response inhibition has been measured during ITL through the Stroop task. The Stroop task, a cognitive task developed by J. Ridley Stroop in 1935, was formulated to assess the cognitive interference effects that arose during inhibition of automated word reading [16]. Stroop evaluates the ability to inhibit automatic responses and is indicative of cognitive control [17]. Deficits in Stroop task performance have been demonstrated in healthy ageing, mild cognitive impairment and dementia [18]. Despite cognitive control being central to the PFC [17], ITL dual-tasking studies have not investigated PFC activation. Thus, a primary objective of this study is to investigate whether the PFC is differentially impacted by rhythmical respiratory muscle or leg activity. This will be assessed through concurrent Stroop task performance, PFC activation and the perceptual response towards ITL or lower limb pedalling. Given dyspnoea's propensity to negatively impact various cognitive processes and the postulated role of dyspnoea competing for cognitive resources, we hypothesised that ITL will result in greater PFC activation, impaired cognitive performance and a heightened perceptual response compared with pedalling.

Materials and methods

Study subjects

Healthy adults (n=30) were recruited from the University of Toronto and surrounding community. Inclusion criteria were 1) 18–50 years, 2) nonsmokers, 3) English fluency, 4) right-handedness confirmed by the Edinburgh Handedness Questionnaire [19], 5) no allergies to adhesives and 6) not colour blind. Exclusion criteria were 1) acute or chronic respiratory, musculoskeletal or neurological conditions, 2) exclusion criteria on the American College of Sports Medicine/American Heart Association pre-participation questionnaire [20] and 3) uncontrolled diabetes and/or high blood pressure. This study was approved by the Health Sciences Research Ethics Board (protocol ID 43144). All participants provided informed consent.

Study design and methods

Participants were asked to refrain from exercise, alcohol and caffeine for 24 h before the testing day. Height, weight and baseline measurements of blood pressure (BP), Borg dyspnoea and RPE were assessed. Spirometry and maximal inspiratory pressures (MIPs) were evaluated. After familiarisation with ITL at 20 cmH_2O, the pedalling intensity of the pedalling device was familiarised to an easy-to-moderate level (2–3 on RPE). During Stroop task familiarisation, an accuracy of 80% was required on a minimum of 20 trials or the familiarisation trial was repeated. Next, participants performed five randomised 3-min blocks of 1) ITL (20 cmH_2O), 2) pedalling, 3) Stroop task, 4) ITL–Stroop and 5) pedalling–Stroop. Stroop stimuli were randomised in every block. BP, Borg dyspnoea and RPE were assessed after each 3-min block. During the rest periods, participants spelled (in their heads) simple three-to-four-letter words from flash cards for 1 min [21].

ITL required participants to breathe through a mouthpiece connected to a two-way nonrebreathing valve (model 1410, Hans Rudolph, Kansas City, MO, USA), with the inspiratory port in series with a heated pneumotachograph (Hans Rudolph) that monitored flow and a positive end-expiratory pressure valve (Ambu PEEP valve, Ballerup, Denmark) positioned in reverse using an inspiratory adaptor (IA 150 Adaptor, Aspire Respiratory Products) [22]. Ports close to the mouthpiece were connected to a differential pressure transducer (MP45, Validyne Corp, Northridge, CA, USA) to evaluate mouth pressure (P_m) and the inlet tubing to a CO_2 gas analyser (Gas Analyzer, ADInstruments, Colorado Springs, CO, USA) to evaluate end-tidal CO_2 ($ETCO_2$) continuously throughout ITL. Inspiratory flow, tidal volume (V_T), minute ventilation (V'_E), respiratory rate (RR), $ETCO_2$, P_m, ECG signals and peripheral oxygen saturation (S_{pO_2}) were acquired and converted to digital signals using a data acquisition device and software (PowerLab/ LabChart, ADInstruments, Colorado Springs, CO, USA).

Pedalling was performed on an under-the-desk device (DeskCycle, CO, USA) for pedalling single and dual tasks. Revolutions per minute (rpm) were measured using the DeskCycle phone application.

The Stroop task was created using PsychoPy (an open-source software package) to record participant reaction time and accuracy [23]. Single-stimulus words (red, blue, green and yellow) were presented on a computer screen in a particular font colour [24] as congruent stimuli when the words matched the font colour (*e.g.* the word "red" in a red font) and incongruent stimuli when the words did not match the font colour (*e.g.* the word "red" in a yellow font). Participants were instructed to press the left or right arrow key on a computer keyboard when presented with congruent or incongruent stimuli, respectively. Colour-word stimuli were presented for 2000 ms interspersed by 500-ms rest intervals for a total of 72 stimuli (3 min) with a 1:1 ratio of congruent to incongruent stimuli.

fNIRS (FNIR100W-1, wireless fNIR Imager System, BIOPAC) measured PFC ΔO_2Hb throughout single and dual tasks. The device has four receiver optodes and two emitters with inter-optode distances of 2.5 cm. Wavelengths of 730 nm and 850 nm were utilised to detect haemoglobin changes. After cleaning the forehead with alcohol swabs, the fNIRS sensor pad was positioned. LED gain settings were adjusted to ensure raw light intensities were within ranges to measure ΔO_2Hb. Data acquisition was conducted using the Cognitive Optical Brain Imaging Studio [25]. A finite impulse response low-pass filter was used to filter physiological artefacts [25] and a sliding-window motion artefact rejection algorithm was used to remove motion artefacts [26]. A modified Beer–Lambert law was applied to measure ΔO_2Hb, with the local baseline being the first 5 s of a given task [26].

MIP was measured at residual volume using a standardised methodology [27] and predicted values (MIP % pred) were calculated [28]. Spirometry was measured using a handheld spirometer (copd-6TM, model 4000, Vitalograph, Ennis, Ireland) using standardised techniques [29] and predicted values [30].

The Depression, Anxiety and Stress Scale-21 (DASS-21) evaluated self-reported depression, anxiety and stress within the past week [31]. This is a 21-item scale that rates emotional state on a 0–3 point Likert scale per item, where 0 indicates no negative emotional state and 3 denotes a maximal negative state.

The Borg dyspnoea scale [32] and RPE [33, 34] were evaluated at baseline and throughout all tasks. Both use a 0–10 category ratio scale with the dyspnoea scale anchored by 0 indicating no breathlessness and 10 indicating maximal breathlessness, whereas the RPE is anchored to words related to exertion rather than breathlessness.

Analysis

Data normality was assessed by the Shapiro–Wilk test. Nonparametric methods were used if the normality assumption was not met. Descriptive statistics were expressed using the median and interquartile range (IQR). The dual-task effect for reaction time and accuracy was calculated as a percentage change from single to dual task, such that a negative change would denote a dual-task cost (DTC) [35]. Two-way repeated measures ANOVA assessed differences between tasks (ITL–Stroop, pedalling–Stroop and Stroop) and congruency stimuli (congruent *versus* incongruent) for the outcomes: reaction time, accuracy and DTC. *Post hoc* tests using the Tukey method to compare estimated marginal means was carried out using the emmeans package in R. The ΔO_2Hb was compared among single and dual tasks in the four PFC regions using Friedman rank-sum test, followed by pairwise comparisons using the Wilcoxon signed-rank test. ITL ventilatory (ITL *versus* ITL–Stroop) and pedalling variables (pedalling *versus* pedalling–Stroop) were compared by Wilcoxon tests. Cardiovascular and Borg variables were compared using a Friedman test followed by pairwise comparisons using the Wilcoxon test where applicable.

Results

Participant characteristics are summarised in table 1. Body mass index and spirometry values were within the normal range. The DASS-21 total and subscores were all within the normal cut-off range.

Greater ΔO_2Hb was shown during ITL–Stroop than during pedalling–Stroop ($p \leq 0.006$) in all PFC regions (figure 1). In addition, ΔO_2Hb was greater during the ITL–Stroop dual task compared with the ITL single task in the right medial PFC (p=0.006) and right dorsolateral PFC (p=0.044) (figure 1).

A two-way ANOVA for reaction time showed a significant effect of tasks (p<0.01) and *post hoc* tests showed that ITL–Stroop (879 ms) had slower reaction times compared with pedalling–Stroop (811.6 ms; p<0.001) and Stroop (798.7 ms; p<0.001) (figure 2). Incongruent stimuli induced a slower mean reaction time (853.7 ms) than congruent stimuli (805.8 ms) (p<0.01) (figure 2).

A two-way repeated measures ANOVA for error showed a significant effect of tasks (p<0.01) and *post hoc* tests showed that ITL–Stroop had greater mean percentage error (4.35%) compared with pedalling–Stroop (2.36%; p=0.006) and Stroop (1.66%; p=0.002) (figure 2). There were no significant effects of congruency (p=0.691) or interaction between tasks and congruency (p=0.344).

A two-way repeated measures ANOVA for the DTCs of reaction time showed a significant effect of tasks (p=0.0017), with ITL–Stroop have greater (more negative) DTC than pedalling–Stroop averaged over congruency (−10.35% *versus* −2.04%, respectively) (figure 3). There was no significant effect of congruency or interaction between congruency and tasks.

A two-way repeated measures ANOVA for the DTCs of accuracy showed a significant effect of tasks (p=0.010), with ITL–Stroop having greater (more negative) DTC than pedalling–Stroop (−2.69% *versus* −0.66%), averaged over congruency (figure 3). There was no significant effect of congruency or interaction.

The ventilatory variables P_m, V'_E, V_T and $ETCO_2$ did not differ during ITL single and dual tasks (table 2). However, RR was lower during ITL dual tasks compared with single tasks (12.6 breaths·min^{-1} (IQR 6.5) *versus* 13.2 breaths·min^{-1} (IQR, 7.4); p=0.027). Pedalling cadence did not differ during single and dual tasks (table 2; p=0.734). However, HR was higher during pedalling single and dual tasks compared with ITL single and dual tasks (p<0.001).

TABLE 1 Baseline characteristics of participants (n=30)

Age, years	23.0 (23.0–24.0)
Males, n (%)	14 (46.7)
Height, cm	169.0 (163.0–173.0)
Weight, kg	64.5 (59.0–73.2)
BMI, kg·m^{-2}	22.9 (21.6–24.3)
MIP, cmH$_2$O	99.0 (83.2–119.2)
MIP, % pred	95.9 (86.9–120.6)
FEV$_1$, L	3.42 (3.15–3.79)
FEV$_1$, % pred	93.9 (87.2–99.6)
FVC, L	4.04 (3.69–4.50)
FVC, % pred	93.5 (87.1–101.0)
FEV$_1$/FVC	0.86 (0.84–0.89)
DASS depression	1.50 (0.0–3.0)
DASS anxiety	1.00 (0.0–2.0)
DASS stress	4.00 (2.25–6.00)

Data are presented as median (interquartile range) unless otherwise stated. BMI: body mass index; MIP: maximal inspiratory pressure; FEV$_1$: forced expiratory volume in 1 s; FVC: forced vital capacity; DASS: depression anxiety stress scale.

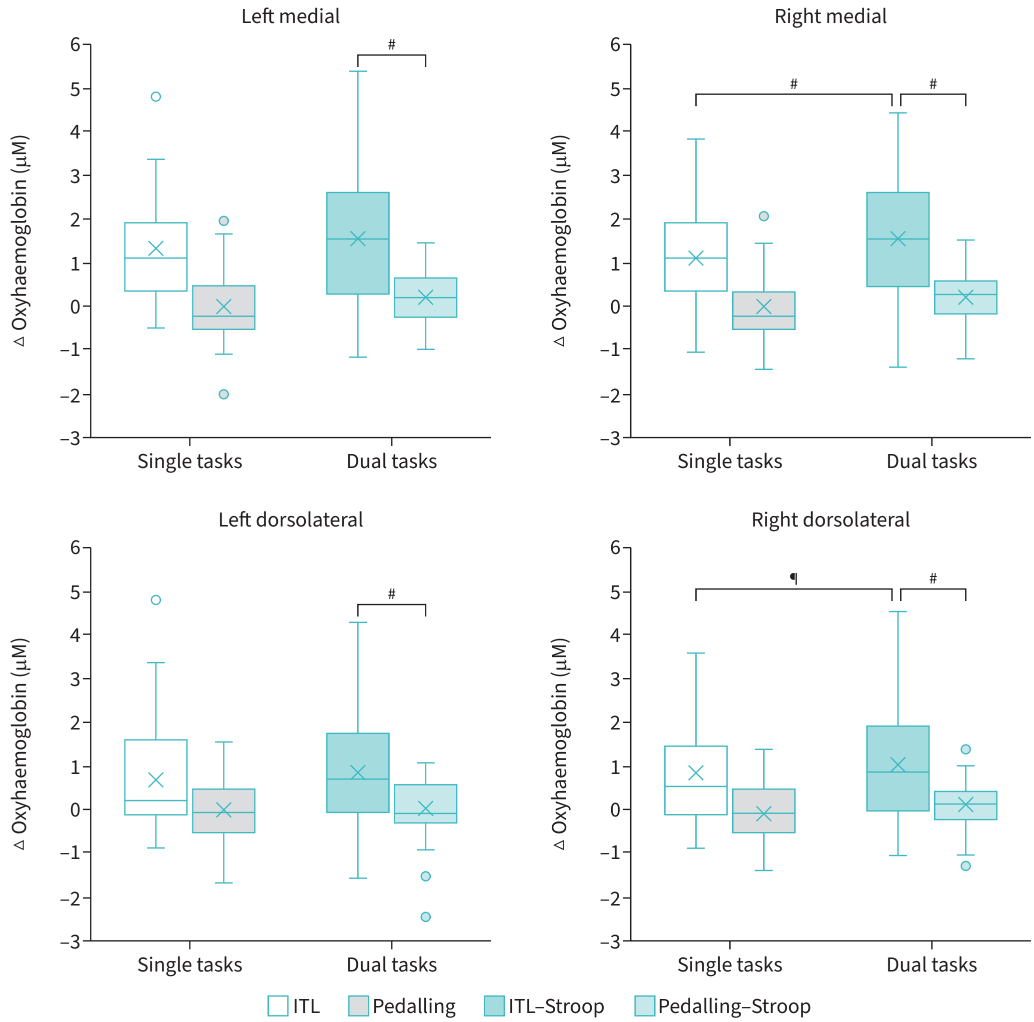

FIGURE 1 Changes (Δ) in oxyhaemoglobin during single and dual tasks in four regions of the prefrontal cortex. For the boxplots, the midline represents the median, the lower and upper dimensions of the box indicate the first and third quartiles, whiskers represent the range and x indicates the mean. ITL: inspiratory threshold loading. #: p⩽0.006; ¶: p=0.044.

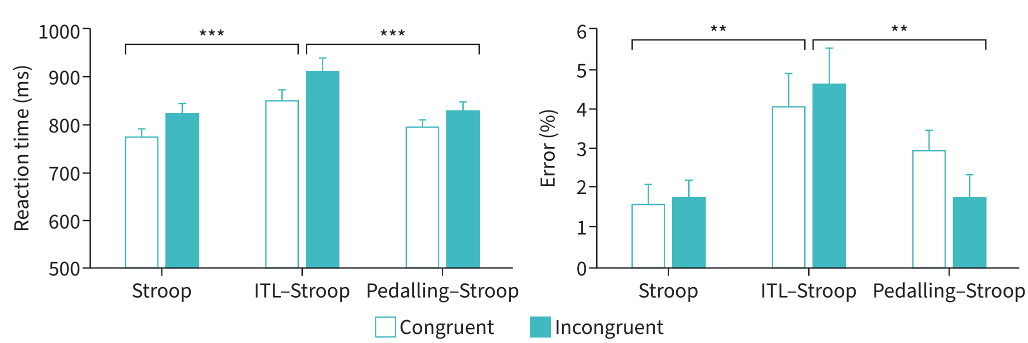

FIGURE 2 Reaction time and error during single and dual tasks. The reaction time (left panel) and error (right panel) during inspiratory threshold loading (ITL)–Stroop averaged over the congruency stimuli were significantly greater than pedalling–Stroop and Stroop. There was no interaction between tasks and congruency. **: p⩽0.01; ***: p<0.001 different from ITL–Stroop.

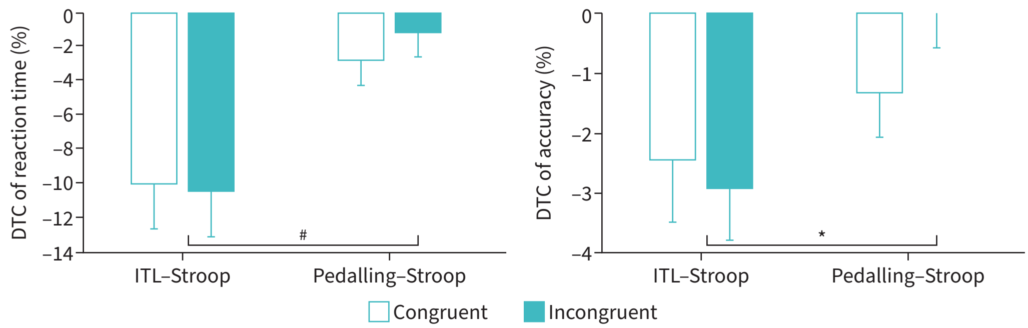

FIGURE 3 Dual task costs for reaction time and accuracy (expressed as %) during inspiratory threshold loading (ITL)–Stroop and pedalling–Stroop. Dual task cost (DTC) for reaction time (left panel) and for accuracy (right panel) during ITL–Stroop was significantly greater (more negative) than during pedalling–Stroop, averaged over congruency stimuli. *: $p<0.05$; #: $p<0.017$.

ITL and ITL–Stroop induced higher Borg dyspnoea and RPE scores compared with pedalling and pedalling–Stroop (table 3) ($p\leqslant0.01$). Baseline dyspnoea, baseline RPE and single-task Stroop values of dyspnoea and RPE were lower from other tasks ($p<0.001$). However, Stroop single-task Borg dyspnoea and RPE were slightly higher than baseline dyspnoea and RPE ($p=0.011$).

Discussion

This is the first study to assess the cognitive and perceptual responses to respiratory muscle and leg activity while measuring PFC activity using fNIRS, while delineating the competing demands of each towards cognitive interference. Our findings are in concordance with our proposed hypotheses. ITL–Stroop elicited greater PFC activation than pedalling–Stroop across all four PFC regions. Moreover, ITL consistently demonstrated a greater decrement in cognitive performance. Furthermore, self-perception evaluations (Borg dyspnoea and RPE) were consistently indicative of more negative affect during ITL–Stroop relative to pedalling–Stroop.

Regarding fNIRS, ITL–Stroop had greater PFC activation than pedalling–Stroop. Along the impaired cognitive performance during ITL–Stroop, the increased PFC activation may indicate that greater attentional

TABLE 2 Characteristics of inspiratory threshold loading and pedalling during single and dual tasks

Variable	ITL	ITL–Stroop	Pedalling	Pedalling–Stroop	p-value
ITL variables					
Mouth pressure, cmH_2O	−19.3 (2.2) (−18.5– −20.7)	−19.0 (1.6) (−18.4– −20.0)			0.305
Minute ventilation, $L\cdot min^{-1}$	20.7 (8.1) (15.6–23.7)	22.9 (8.1) (17.1–25.2)			0.179
Tidal volume, L	1.4 (0.8) (1.2–2.0)	1.4 (0.7) (1.1–1.8)			0.716
Respiratory rate, $breaths\cdot min^{-1}$	13.2 (7.4) (9.3–16.7)	12.6 (6.5) (11.6–18.1)			**0.027**
End-tidal CO_2, mmHg	30.4 (6.0) (27.8–33.8)	30.5 (6.8) (28.5–35.3)			0.305
Pedalling variable					
Pedalling cadence, rpm			57.0 (20.5)	60.2 (13.7)	0.734
Cardiovascular variables					
Heart rate, bpm	75.6 (18.4) (67.7–86.1)	76.2 (13.6)[#] (72.0–85.6)	86.8 (8.1)[#,¶] (82.2–90.3)	86.3 (16.4)[#,¶] (80.7–97.1)	**<0.001**
Mean blood pressure, mmHg	89.3 (15.1) (79.7–94.8)	87.2 (9.0) (81.9–90.9)	90.0 (13.5) (81.8–95.3)	87.3 (14.2) (80.2–94.4)	0.439

Data are presented as median (interquartile range) (lower and upper quartile). p-values indicate differences for paired comparisons by Wilcoxon test or across all comparisons for heart rate and mean blood pressure by Friedman test. If differences were found by the Friedman test, a Wilcoxon test was performed for paired comparisons. ITL: inspiratory threshold loading; rpm: revolutions per minute; bpm: beats per minute. #: different from ITL; ¶: different from ITL–Stroop. Bold indicates statistically significant p-values.

TABLE 3 Borg dyspnoea and rating of perceived exertion

Measure	Baseline	Stroop	ITL	ITL–Stroop	Pedalling	Pedalling–Stroop
Dyspnoea	0.0 (0.0)*** (0.0–0.0)	0.0 (0.5)*** (0.0–0.5)	3.0 (1.5)# (1.75–3.25)	3.0 (3.0)# (1.0–4.0)	1.0 (1.5) (0.5–2.0)	1.0 (1.5) (0.5–2.0)
RPE	0.0 (0.0)*** (0.0–0.0)	0.0 (1.0)*** (0.0–1.0)	3.0 (1.0)¶ (2.0–3.0)	3.0 (2.0)# (2.0–4.00)	2.0 (1.25) (1.0–2.25)	2.0 (1.25) (1.75–3.0)

Data are presented as median (interquartile range) (lower and upper quartile). After significance was shown by the Friedman rank-sum test, pairwise comparisons were conducted using the Wilcoxon test. ITL: inspiratory threshold loading; RPE: rating of perceived exertion. ***: p<0.001 *versus* other tasks; #: p<0.001 *versus* pedalling and pedalling–Stroop; ¶: p=0.005 *versus* pedalling and pedalling–Stroop.

demands are required during ITL–Stroop. Indeed, the attentional requirements for ITL are corroborated by previous studies that found impairments in attention-related tests during ITL dual tasking [6, 36]. Furthermore, our fNIRS findings depict both the right medial and right dorsolateral PFC to have increased ΔO_2Hb during ITL–Stroop compared with single-task ITL. Thus, with respect to our sample, the right PFC may be pivotal in the concomitant performance of loaded breathing and Stroop. Accordingly, repetitive transcranial magnetic stimulation over the right dorsolateral PFC has been shown to impair adaptive control during the Stroop task [37]. Additionally, participants with right PFC lesions were found to have decreased accuracy in the Stroop task, suggesting the importance of this region to attention [38]. Thus, the increased right PFC activation seen in our study may reflect the overlap in capacity required for Stroop task performance and respiratory-related cortical activation.

Interestingly, there was a greater perceptual response of Borg dyspnoea and RPE during the ITL single and dual tasks, despite the pedalling tasks eliciting a greater cardiovascular response (increased HR). This suggests that the perception of effort, particularly when associated with dyspnoea, cannot be fully discerned by peripheral physiological parameters such as HR. While the Borg RPE was initially developed with its connections with HR, perception of effort is not necessarily causally related to HR [8]. This has been shown in patients with chronic atrial fibrillation during exercise, whereby administration of β-adrenergic or calcium channel blockers did not correspond to a change in RPE or increased RPE, despite lowering HR, compared with placebo [39]. Importantly, in our study the increased perceptual response to dyspnoea was also reflected in the decrements in cognitive performance.

As described, pedalling was adjusted to a mild-to-moderate intensity such that pedalling was performed with a similar load (while minimising dyspnoea) as ITL. Our findings regarding ITL impairing response inhibition are partially concomitant with a previous study that investigated Stroop task performance while performing ITL in healthy participants [5]. The previous study found that ITL impaired accuracy, but their two-way repeated measures ANOVA for reaction time did not demonstrate a significant effect of single *versus* dual task [5]. A potential difference is that their peak pressure threshold was -10.08 cmH_2O (SD 4.40), whereas our median load was -19.0 cmH_2O (IQR 1.6). A previous functional magnetic resonance imaging study observed that 3 min of ITL using a median pressure threshold load of 10 cmH_2O induced cortical automaticity, whereby blood oxygen level-dependent signal changes were seen in few regions, indicative of fewer attentional requirements [40]. More specifically, automaticity, typically seen during certain well-learned motor tasks such as walking, is the set of automatic cognitive processes that require less executive and cognitive control [41]. Thus, the overall impact that loaded breathing and the accompanied dyspnoea has on cognitive performance may depend on the level of applied threshold load, and whether more attention-dependent mechanisms are required with higher loads remains to be fully understood. However, a previous fNIRS study investigating the PFC response to incremental ITL, found increased ΔO_2Hb at task failure [14]. Consequently, increased attention-dependent mechanisms, insofar as PFC activation is indicative of them, may be a function of intensity of pressure threshold load and time sustained under loaded breathing.

Regarding the Stroop task congruency stimuli, we found a significant effect of congruency for reaction time, where incongruent stimuli had slower reaction times than congruent stimuli. This was similar to the observed significant effect of congruency found by SUCEC *et al.* [5]. However, our study did not find a significant effect of congruency for Stroop task accuracy. While there was a realisation of the Stroop effect regarding reaction time [24], the insignificant influence of congruency on accuracy may be in part due to methodology, specifically with regards to our 1:1 congruency ratio. Increasing the ratio of congruent to incongruent stimuli (*e.g.* 3:1 congruent to incongruent) in a mixed block of Stroop stimuli has been shown to potentiate the Stroop effect [18].

Although, our findings and those of Sucec *et al.* [5] demonstrate ITL impairing Stroop task performance, another study in healthy participants found that ITL did not impair Stroop task performance [7]. The differences may be due to Stroop stimuli presentation; our study and that of Sucec *et al.* [5] presented four-colour-word stimuli, whereas Vinckier *et al.* [7] only utilised two-colour-word stimuli. Moreover, the study was exploratory and only recruited 12 participants [7]. Interestingly, they also performed a motor dual task and found that it impaired Stroop task reaction time more than ITL [7]. The motor task entailed pressing a pedal with the participant's left foot rhythmically; however, the protocol did not state whether they assessed footedness [7]. Thus, greater interference may have arisen depending on the subject's foot preference.

Our findings delineating the greater contribution of ITL and associated dyspnoea compared with pedalling towards PFC activity, cognition and effort perception are relevant to the context of patients with heightened dyspnoea perception. For instance, patients with respiratory exacerbations [42] or refractory dyspnoea [43] have a diminished function in performing ADLs. While peripheral muscle deconditioning may influence these patient's ADLs [44], our findings depict dyspnoea as potentially having a greater cognitive burden and thereby mitigating the performance of concomitant tasks. Indeed, cognitive impairment is prevalent in patients with COPD with acute exacerbations during hospitalisation and post-discharge [45]. Additionally, patients with respiratory exacerbations [46] or refractory dyspnoea [43] also exhibit greater negative effects, such as anxiety. Anxiety has been shown to be linked to frontal cortex activation [47] and higher-order neural processing [48] during experimental inspiratory occlusions. Thus, dyspnoea's cognitive-affective influence would potentially negatively impact the neural resources needed for multitask scenarios.

There are limitations with this study. First, our sample was a young population, and this may have influenced performance. Recruitment occurred during concerns about COVID-19, which limited recruitment of older populations and those with chronic respiratory disease. A second limitation is that we utilised the Borg RPE to help guide low-to-moderate pedalling intensity. Adjusting pedalling intensity to a percentage of a participant's maximal oxygen consumption would have enabled more accurate cardiorespiratory quantification of intensity. Other limitations include factors that may potentially impact our ΔO_2Hb findings by influencing intracerebral and extracerebral haemodynamics, such as changes in $ETCO_2$ and HR [49]. Hypocapnia leads to cerebral vasoconstriction and subsequently a decrease in cerebral blood flow [50]. However, despite the ITL-associated decrease in $ETCO_2$, the ITL tasks still demonstrated increased ΔO_2Hb relative to the pedalling tasks. Additionally, HR has been shown to be correlated with frontal lobe activity [51] and can influence scalp blood flow [52]. Future initiatives to mitigate physiological noise may include expanding our multimodal monitoring by including measures of autonomic nervous system activity, scalp blood flow and addition of extra short fNIRS channels to allow extraction of extracerebral influence [49].

In conclusion, respiratory muscle loading elicited by ITL has a greater negative impact on response inhibition and reaction time than pedalling. The increased PFC activation seen during ITL dual tasking may indicate increased cognitive capacity requirements elicited by loaded breathing associated with dyspnoea, the heightened perception of effort and sustained attention. Future studies should investigate older adults or patient populations to reveal the extent of these findings.

Provenance: Submitted article, peer reviewed.

Ethics statement: Our study was on healthy adults; therefore, ethics approval was required. The Health Sciences Research Ethics Board gave approval.

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