# BreathePulse: Peripheral Guided Breathing via Implicit Airflow Cues for Information Work

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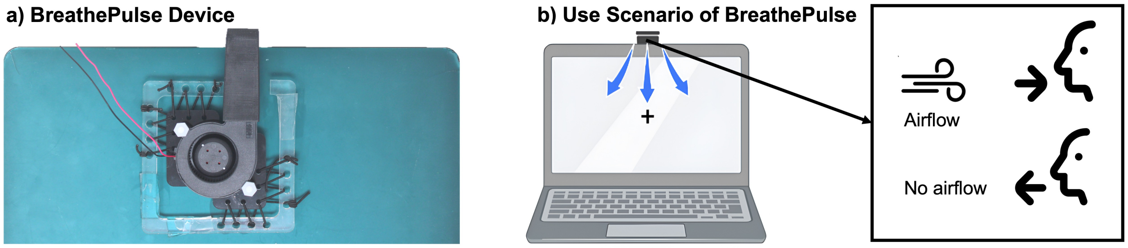

Fig. 1. (a) BreathePulse is a peripheral breathing guide. It mounts on the back of a laptop. (b) While the user performs a primary task on the laptop, BreathePulse uses subtle airflow cues to guide breathing: the user inhales when they feel the airflow, and exhales when they don't.

Workplace stress contributes to poor performance and adverse health outcomes, yet current stress management tools often fall short in the fast-paced modern workforce. Guided slow breathing is a promising intervention for stress and anxiety, with peripheral breathing guides being explored for concurrent task use. However, their need for explicit user engagement underscores the need for more seamless, implicit interventions optimized for workplaces. In this mixed-method, controlled study, we examined the feasibility and effects of BreathePulse, a laptop-mounted device that delivers pulsing airflow to the nostrils as an implicit cue, on stress, anxiety, affect, and workload during two levels of a memory (N-Back) task with

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23 participants. We found that BreathePulse, the first airflow-only breathing guide, effectively promoted slow breathing, particularly during the easy memory task. Participants' breathing rates aligned with BreathePulse's guidance across tasks, with the longest maintenance of slow breathing – over 40% of the time – during the easy task. Although BreathePulse increased workload and had little impact on stress, it promoted mindfulness, indicating its potential for stress management in the workplace.

CCS Concepts: • **Human-centered computing → Empirical studies in ubiquitous and mobile computing**; • **Applied computing** → *Psychology*.

Additional Key Words and Phrases: guided breathing, slow breathing, respiration, intervention, airflow

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## 1 INTRODUCTION

Workplace stress has been linked to poor health outcomes (anxiety, depression, fatigue) [56] and adverse work results such as higher turnover and lower satisfaction [21]. Mobile and ubiquitous technology have focused on delivering mindfulness practices, therapy, and psycho-education digitally [11]. However, these interventions require taking breaks from work, which nearly half of global information workers cannot take [52]. As workers are more likely to complete just-in-time interventions than those requiring time away from tasks [20], there is a need for effective, in-the-moment stress interventions that do not demand additional attention or time.

Slow, deep breathing is an effective intervention for stress relief and anxiety [2] applicable in different contexts [13], from everyday practice to clinical treatment [2]. The human-computer interaction (HCI) community has developed *peripheral breathing guides*, systems providing breathing guidance concurrently with other tasks [39, 57], delivering tactile [10, 36, 65], visual [15, 38], or auditory cues [4] to achieve lower target respiratory rate.

Peripheral breathing guides can be effective workplace stress interventions, especially for information work [40]. However, current guides conceptualize breathing as an explicit task: While performing a primary task such as writing emails or preparing presentations, users interrupt their routine workflow to consciously change their breathing pattern in response to explicit cues from a breathing guide. The explicit nature of both the breathing cues and the breathing task contrasts with the application of breathing guides as an unobtrusive intervention for workplace stress. Thus, there needs to be a way to *implicitly* guide breathing without interfering with primary work tasks.

Evaluating the workload due to workplace breathing interventions is also critical. While it's agreed that users can follow peripheral breathing guides, existing guides often overlook the workload the breathing guide adds to the primary task and intervention effectiveness under different intensities of the primary task. The few studies that characterize the workload of the breathing intervention [9, 57] have not assessed the workload when using a breathing guide concurrently with a primary task.

In this study, we designed BreathePulse – a peripheral breathing guide that uses subtle, pulsing airflow – and evaluated its feasibility and effects on momentary psychological and physiological stress during information work. We choose airflow as a modality because it maps seamlessly to breathing itself. Through this device, we explored an alternative approach for guided breathing: using **implicit** cues that blend into the environment so that the user can implicitly follow the guide while performing cognitively demanding work tasks. The device is positioned at the top of the laptop and emits gentle airflow cues near the user's mouth and nose. When airflow is present, the user is cued to inhale; when it is absent, to exhale, guiding them to breathe at about 75% of their normal breathing rate.

To evaluate the impact of implicit guided breathing during cognitive tasks with various workloads, we conducted a controlled mixed-method laboratory study with 23 participants. Participants were cognitively loaded using two levels of a memory task (N-Back) while receiving breathing guidance. We aimed to answer the following research questions:

- RQ1: Can users breathe with an implicit airflow guide while performing a primary task?
- RQ2: How much workload is associated with breathing with the airflow guide?
- RQ3: How does breathing with the airflow guide affect in-the-moment stress, anxiety, and affect while the user performs a primary task?

Our findings indicate that participants were able to breathe slowly with BreathePulse. However, doing so with information work increased workload, suggesting that breathing with the airflow guide was not implicit in a controlled lab setting. BreathePulse demonstrates the potential of airflow as a modality for guided breathing to promote mindfulness, particularly during less demanding tasks.

We conducted empirical evaluations detailing the feasibility, workload, and impact of using BreathePulse for implicit guided breathing concurrently with a cognitive task of multiple workload levels. Through our evaluation, we make three main contributions to HCI and behavioral health interventions:

- We designed, to the best of our knowledge, the first guided breathing system using airflow as the only modality.
- We found that BreathePulse lowered respiratory rate across both easy and difficult primary tasks to different degrees without compromising task performance. In addition, although the airflow guide had little impact on stress, it promoted mindfulness.
- We quantified the additive impact of peripheral breathing guides on mental workload by evaluating workload during cognitive tasks with and without breathing guidance, unlike past studies. Based on qualitative feedback, we identified that salience and attention were critical factors in the workload increase.

We reflected on these findings to obtain design guidelines for HCI and behavioral health researchers to design guided breathing devices while considering workload as a resource.

## 2 RELATED WORK

### 2.1 Guided Breathing as Stress Intervention

“Take a deep breath” is common advice in stressful situations. Unlike other physiological processes involved in stress response (heart rate, blood pressure, etc.), respiration can be voluntarily controlled and slowed down. Slow, deep breathing (6-8 breaths per minute) briefly increases blood oxygenation and lowers blood pressure, triggering an arterial reflex that stimulates the vagus nerve – a large nerve that oversees control of mood, immune response, digestion, and heart rate – leading to a state of calm [47]. Subjectively, slow breathing was shown [67] to *promote* comfort, relaxation [28], pleasantness, vigor and alertness [14]; at the same time, it can *decrease* symptoms of arousal [59], anxiety [16, 42], depression [66], anger, and confusion [14]. While achieving the optimal [26] 4-6 breaths per minute (bpm) requires focused breathing practice, physiological and psychological benefits can occur even at 8-10 bpm [47, 54], more easily achievable in everyday conditions.

### 2.2 Unobtrusive Stress Intervention for Information Work

Current mobile-health (mHealth) stress interventions for the workplace primarily consist of mindfulness and meditation apps, cognitive-behavioral therapy (CBT) programs, and stress management tools delivered through smartphone applications and web-based platforms [11, 61]. While these interventions can significantly reduce perceived stress and enhance well-being over time [25, 63], the effects are generally small [55]. Challenges of mHealth interventions for workplace stress includes time constraints [7, 41, 52], workplace environment (e.g., open workspace) [7], and lack of integration to policies [41].

To make workplace stress interventions more integrated to the workflow and require less time to use, researchers investigated just-in-time stress interventions. Just-in-time interventions allow information workers to engage with interventions more often [20, 48, 53]. However, these just-in-time interventions still used digital interventions that disrupted ongoing tasks, resulting in workers concentrating on using interventions at the beginning of the day [48] with limited long-term impact [20]. There's a need to develop more unobtrusive interventions that information workers can engage in without disrupting their flow.

## 2.3 Peripheral Guided Breathing

The potential of guided breathing attracted much research interest in the HCI community. Researchers have tried various modalities for intervention delivery, including audio [4, 31], visual [15, 38], and haptic [10, 36, 43, 65]; these have been studied in a variety of scenarios, including virtual environments [45], driving [1, 24, 44], information work [57]. Increasingly, these devices have been personalized to the breathing patterns of their user [35, 58] but their interaction paradigms have diverged into guided breathing as a deliberate, active task [18, 23, 51] vs. guided breathing as a peripheral, implicit phenomenon [24, 57].

Peripheral guided breathing enables users to mitigate stress while engaged in another activity (typically information work [15, 33, 38, 57] or driving [1, 24, 44]. There are two approaches to make the breathing guide "peripheral". One approach is integrating the breathing guide in a form factor within the primary activity contexts – for example, as a bar going across the computer screen to pace breathing [39] or color gradient animation in the periphery of the browsing window [33]. The other way is to develop ambient technology that tangibly exists in the peripheral attention of the user and seamlessly merges with the user's environment [10, 15].

Researchers have investigated visual [5, 33, 38], auditory [27], haptic [10], and multi-sensory [15] approaches to peripheral breathing guides. Additionally, multiple evaluations focused on comparing different modalities on desktop [57] and in car [1, 24, 44] and comparing one modality across different contexts [9]. The consensus among these studies is three-fold. All modalities can reduce respiratory rate, with higher levels of reduction in-car [1, 44]than in desktop work [27, 39, 57]. However, regardless of modality, the adherence rate to peripheral breathing guides is around 30% [57] for desktop work, while the adherence rate for in-car contexts is unknown. Moreover, not all changes in respiratory rate lead to lowered stress [24, 44, 57] or better performance [15, 24]. To improve the design of peripheral guided breathing, Tabor et al. recommended designing breathing guides with more natural mapping to bodily sensations (e.g., inhale and exhale movements, inflow and outflow of air) [57]. Only limited work investigated the workload associated with using the peripheral breathing guide, with results ranging from no significant difference among modalities in car [24], and audio, haptic, and object animation requiring less workload than brightness change during information work [57]. We summarize the results of selected peripheral breathing guides in Figure 2.

The current state-of-the-art of peripheral guided breathing needs to map more naturally to the bodily sensation. Additionally, the workload added by breathing guides has been overlooked, leaving inconclusive observations on stress levels and task performance. In our investigation, we designed an airflow-based device for peripheral breathing guidance. Unlike prior devices, we focused on directly delivering airflow cues (instead of indirect cues that need to be associated with breathing but are not intrinsically part of breathing). This enables a more natural mapping to the bodily sensation of breathing while paying close attention to workload associated with following the breathing guide in different contexts.

In this work, we explore airflow as a modality because it seamlessly maps to breathing itself [57]. It also achieves the best performance in lowering breath rate and ease of use in prior work [24].

| Title | Modality | Context | Sample Size | Respiratory Rate Reduction | Adherence | Workload | Stress and Anxiety | Task Performance |
|---|---|---|---|---|---|---|---|---|
| BreathePulse (this work) | Airflow | Information Work | 23 | Respiratory rate reduced by 4.04 BPM for no primary task (24.5%), 2.41 BPM with easy primary task (15.4%), and 1.31 BPM for hard primary task (8.5%) | 41.5% of time spent under goal breathing rate for easy primary task, 27.5% of time spent under goal breathing rate for hard primary task | Airflow guide increased workload for both easy and hard primary tasks | No significant effect on HRV-RMSSD | No significant effect on task performance |
| Just Breathe (2018) | Haptic (vibrotactile), Audio (voice) | Driving | 24 | Both modalities reduced respiratory rate (50% reduction during intervention, 40% reduction after intervention) | - | Haptic guide less distracting than voice | Increase HRV-RMSSD during intervention for both modalities | No significant effect on driving performance and safety |
| Calm Commute (2020) | Haptic (vibrotactile) | Driving | 24 | Respiratory rate reduced by 15.94% during normal driving and 25.34 % during post-stressor driving (target being 30% reduction) | - | - | No significant effect for normal driving; significant increase in HRV-RMSSD for post-stressor driving | No significant difference on driving performance |
| AmbientBreath (2021) | Visual (light), Audio (white noise), Airflow | Driving | 54 | No significant effect on normalized respiratory rate without training, but significant effect with training. | No significant effect on adherence without training, but significant effect with training (45% increase of time spent under goal breathing rate) | No significant difference in workload with or without intervention, and with or without training | Significant reduction of EDA with training | - |
| Tabor et al. (2021) | Visual (object animation, screen brightness, desk-widget brightness), Audio (music note), Haptic (vibrotactile) | Information Work | 25 | Respiratory rate reduced by 4.8 BPM but the actual respiratory rate is significantly different from goal breathing rate | 28% of time aligned with guide (range from 20.4% - 32.8%) | Audio, haptic, and object animation requires less effort than screen and widget brightness | Increased HRV-SDNN with breathing guide and with time | Significant effect of order |
| Choi et al. (2022) | Haptic (pneumatic) | Driving, Information Work, Walking | 40 | No group-level results | No group-level results | Workload of both haptic design are comparable to no intervention (n.s.) | No significant effect on EDA | - |
| BrightBeat (2017) | Visual (screen brightness), Audio (volume), Haptic (wrist temperature) | Information Work | 32 | - | 40-60% of time spent in goal breathing rate | - | Increased self-reported calmness | No significant difference |
| Leslie et al. (2019) | Audio (music) | Reaction Time Task | 19 | Higher z-score of inter-respiration intervals and higher breathing variability during intervention | - | - | No significant change in HRV. Decreased EDA with personalized tempo breathing guide. | - |
| Moraveji et al. (2011) | Visual (object animation, screen brightness) | Information Work | 13 | Respiratory rate reduced by 1.8 BPM | | - | - | - |

Fig. 2. The results of prior peripheral breathing guides. Most guides were able to reduce respiratory rate. However, few works investigated the adherence to the breathing guide with varied metrics. Workload evaluations focused on comparing modalities, but little is known about how much peripheral breathing guides added to the primary task, especially for information work.

# 3 DESIGN OF AIRFLOW-GUIDED BREATHING DEVICE

## 3.1 Design Rationale

Breathing guidance devices have increasingly used contact-based wearable modalities such as vibrotactile or pneumatic haptics [9, 36]. However, these wearables can be uncomfortable due to the tactile sensation, weight, and physical constraints. When users are stationary, like during information work, ubiquitous non-contact methods can be a less-encumbering alternative. Existing non-contact modalities for breathing guidance, like light or audio, can be distracting, especially for visual and auditory tasks common in information work settings [57, 64]. In contrast with these modalities, airflow has only been investigated as a supplementary signal alongside an auditory intervention [24]. Notably, in the study by Lee et al. as a supplementary signal, combining audio with airflow was the users' most preferred intervention option.

Airflow provides a direct mapping to not only the pattern of breathing, but also the action. Air flows in through the nose or mouth during inhalation, while exhalation reverses the airflow to expel the air. To mimic this pattern, BreathePulse uses a fan that produces a stream of air during inhalation, and turns off during exhalation. As noted by Tabor et al., replicating intrinsic bodily movements creates a more natural mapping and increases ease of use [57]. We directed the air stream to the nose, seeking to encourage nasal inhalation and create a flow-based sensation in the nose beyond the tactile sensation on the skin. When testing different locations pointed to the nose from the desktop, we found that the top of a laptop screen – typically occupied by a web camera – is often aligned with users' noses when they have a healthy sitting posture. BreathePulse includes an air nozzle at this location, providing airflow-based breathing guidance in a ubiquitous and mobile configuration suitable for information work.

BreathePulse provides significant advantages for the deployment and use of breathing guidance in information work. The overall system costs only $20 (including fan, electronics, and air nozzle) and takes up little space. The device location and fan strength can be adapted based on user needs. The duration of use is flexible, as users can turn the device on intermittently or keep it on throughout a workday.

### 3.2 Device Design

BreathePulse is a hardware device designed to be mounted on different surfaces. Its most immediate application is enabled by mounting it on the back of a laptop screen, enabling the device to provide peripheral slow breathing guides to a user in front of the screen, as shown in Figure 3a – we deliberately designed for and focused on this form-factor given its fit towards our aim of interventions for workplace settings. The core of the BreathePulse device is a disk fan (Delta Fan Delta PBT-GF30) and an air nozzle, shown in (Figure 3b, concentrating the air moments toward the participants' nostrils. The nozzle's exit occupies the location typically occupied by laptop cameras, making it convenient to aim at the center of a user's face by modifying the screen angle or table height. The fan is controlled by a motor driver (Adafruit DRV8871), which controls the fan, and a microcontroller (Adafruit RP2040), which controls the air pulsing frequency based on each participant's baseline respiratory rate. For convenience during the study, we also included three buttons the experimenter could use to switch between three fan conditions: constant airflow, pulsing airflow, and no airflow. An LED next to the buttons shows the current selected condition. These electronics are powered by an AC adapter that converts wall power to 12 V.

### 3.3 Intervention Delivery

The BreathePulse device was designed to generate a subtle stream of air to guide slow, deep breathing. The strength of the fan we used is just enough for the airflow to be perceptible and easy to ignore when the user does not pay attention to the airflow. The intervention is delivered through a fan that can be switched to three different settings:

1. *No Airflow (NA):* The fan is turned off and does not generate any airflow. This setting stands for a negative control for the experiment, assessing any outcomes that are independent from any airflow-based intervention.
2. *Constant Airflow (CA):* The fan is *always on* and generates a continuous air stream. This setting stands for a positive control for the experiment to understand the effect of adding airflow, but without pulsing it.

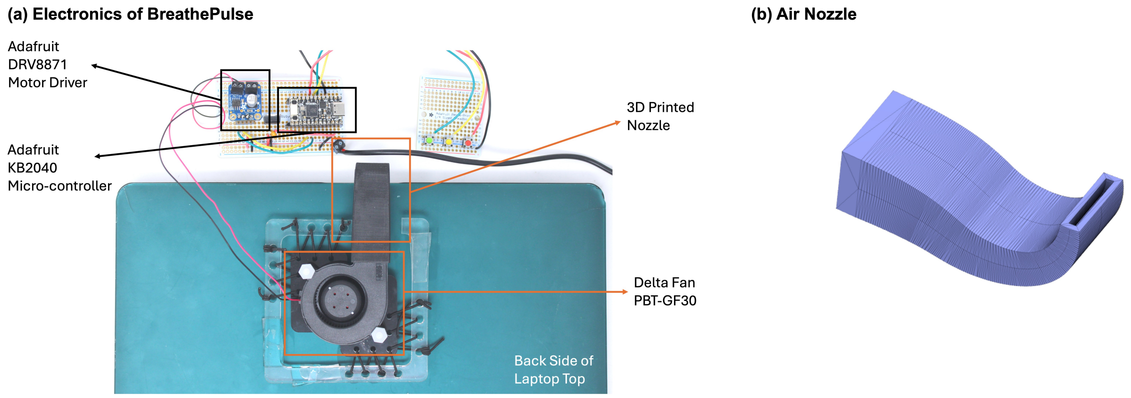

Fig. 3. The BreathePulse device mounts on the back of the laptop (a). The air nozzle concentrates the airflow and directs it at the user's nostrils (b).

(3) *Pulsing Airflow (PA):* The fan alternates on and off in a square wave pattern, generating airflow and then stopping cyclically. Based on a target rate of 75% of the user's baseline breathing rate, the fan completes one square wave cycle in sync with one inhale and exhale cycle when breathing at the target rate. Prior work found 75% to be the most efficient personalized breathing rate for encouraging slow breathing [1, 10, 27]. This setting is the intended intervention of BreathePulse.

## 4 METHODS

### 4.1 Participants

The current study was approved by Cornell University's IRB (IRB0010360). We recruited 37 participants via study flyers distributed on campus and electronically to local community groups on social media platforms (e.g., Slack channels, Facebook groups) from September 2023 to April 2024. Eligible participants were 18 years old or older, fluent in English, and did not have current or previous respiratory or breathing-related problems. All participants provided written informed consent, completed a 1.5-hour study session, and received $30 for their participation. Out of the 37 enrolled participants, 30 completed the questionnaires, 24 had valid respiratory rate data, and 29 had valid heart rate variability (HRV) data. We considered participants whose respiratory rates during baseline were below 5 bpm to be invalid. In addition, we considered participants whose HRV data was lost or too noisy to process to be invalid. Our quantitative analyses only included participants with all valid data (n=23). The sample included individuals aged 22 to 52 ($M = 30.83, SD = 7.58$), comprising nine men, two non-binary individuals, and 12 women from Asian (14), Black/African-American (1), Hispanic (2), and White/Caucasian (6) racial/ethnic backgrounds.

*4.1.1 Sample Size Determination.* An a priori power analysis was performed with G*Power version 3.1 [12] to identify the minimal number of participants needed to evaluate the effect of BreathePulse adequately. To achieve 85% power for detecting a medium-sized effect of 0.25 with a significance level of $\alpha = 0.05$, a sample size of N = 21 is necessary for F tests with repeated measures and within factors. Consequently, the achieved sample size of N = 23 is sufficient for examining the study's hypotheses.

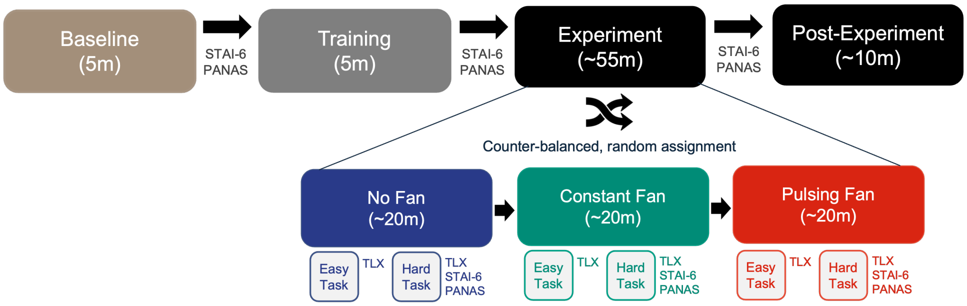

Fig. 4. Overview of the study design. This repeated measures study consisted of four phases: baseline, training, experiment, and post-experiment. All participants were exposed to each experimental condition in a randomized and counterbalanced sequence.

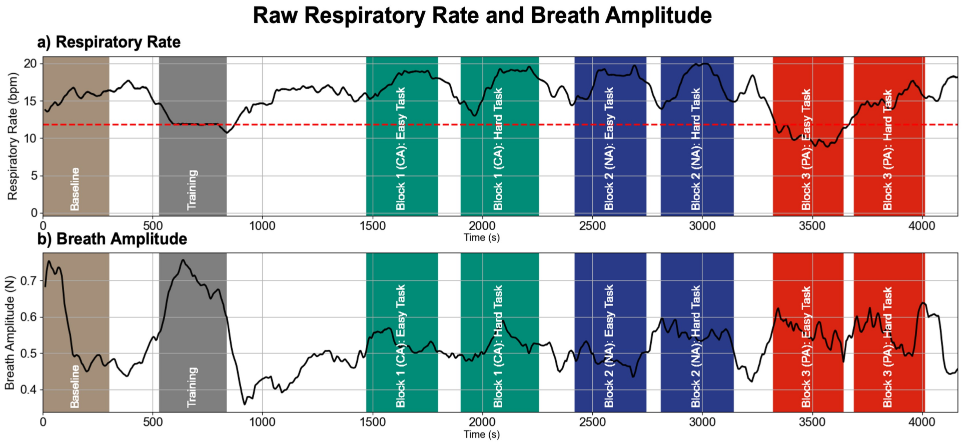

Fig. 5. The trend of respiratory rate and breath amplitude of a sample participant across the study session. The red dashed line for respiratory rate represents the target respiratory rate.

## 4.2 Study Design

The study session was structured into four phases: baseline (BL), training (TR), experiment, and post-experiment, as illustrated in Figure 4. It included three experimental conditions: (1) no airflow (NA), (2) pulsing airflow (PA), and (3) constant airflow (CA). The study employed a within-subjects experimental design to examine users' ability (RQ1) and workload (RQ2) to breathe with the pulsing airflow from the BreathePulse device as well as the impact of this airflow-based slow breathing on momentary psychological and physiological stress/relaxation (RQ3). Participants experienced these conditions in a counterbalanced order to minimize order effects, with assignments as follows: NA-PA-CA (four participants), NA-CA-PA (three), PA-NA-CA (three), PA-CA-NA (five), CA-PA-NA (four), and CA-NA-PA (four). Figure 5 illustrates the respiratory rate and breath amplitude trend of a single participant in the CA-NA-PA order across the study session. The primary dependent variables evaluated in this study included respiratory rate (RQ1), mental and physical demand, frustration, effort, perceived reduced performance, and total workload (RQ2), and psychological relaxation reported via state-level anxiety and affect questionnaires and physiological relaxation measured by heart rate variability (HRV; RQ3).

Fig. 6. The study apparatus includes the *BreathePulse* device that blows a subtle airflow to guide slow breathing. The air nozzle is placed on top of the laptop screen and directs the airflow to the participant's nostrils. Participants wear the Vernier Go Direct Respiration Belt around the chest to collect the respiratory rate. Participant also wears the Polar H10 heart rate monitor under the clothes to collect the ECG.

## 4.3 Measures

### *4.3.1 Physiological Measures.*

*Respiratory Rate.* The Vernier Go Direct Respiration Belt [60] was used to monitor participants' respiratory rates by capturing chest movement through force measurements up to 50N at 10Hz and respiratory rates at 0.1Hz. However, initial tests showed the belt's respiratory rate data to be unreliable, so we derived respiratory rate measurements from raw force data.

We calculated respiratory rates in breaths per minute (bpm) by counting chest rises within a given duration, typically ranging from 12 to 20 bpm in adults [34]. We applied a third-order Butterworth filter with a lower cutoff at 0.1Hz and 0.5Hz to the force data, which maps to a 6 to 30 bpm range that includes the normal range and its periphery. Then, we extracted a window for the duration of force data within each phase of the experiment and applied peak detection with SciPy to determine the prominent (prominence=0.5, distance=10) peaks. We counted the number of prominent peaks and divided it by the window duration to get the respiratory rate for each phase of the experiment. Our respiratory rate estimation process is based on past sensing studies that have successfully used the Go Direct Respiration Belt to get high-accuracy (above 90%) results [19].

Participants' baseline respiratory rate was measured at the study onset during a five-minute period where participants sat still and watched a video. We calculated the baseline respiratory rate in real-time using a five-minute window. We used each participant's baseline respiratory rate to personalize their pulsing airflow in the training and pulsing airflow condition, setting the fan speed to 75% of each participant's baseline rate (further details in Section 4.4).

*Breathing Amplitude.* During the peak detection process for obtaining respiratory rate, we also extracted the highest force value at each peak as the respiratory force. As the mean respiratory force can be skewed by anomalous peak forces from non-breathing movements such as posture adjustments, we chose to calculate median respiratory force instead, eliminating the need for outlier exclusion on force values. This approach provided an amplitude of breathing force. While reporting on this metric is limited, some prior studies have used it to assess whether participants were breathing deeply in addition to slowly [9, 37]. While other measures like chest radius change and tidal volume can indicate breathing depth or amplitude, using amplitude of force was the most accessible method for our study.

*Percentage of Time in Slow Breathing.* We were also interested in how often participants breathed slower than their baseline within the pulsing airflow condition. We used a 30-second moving window to calculate the respiratory rate for different subsections of the data in each phase. The 30-second moving window to calculate respiratory rate was based on Tabor et al. [57] and Choi et al.'s [9] work, which used 15-second and 45-second windows respectively. Since several participants had close to 10 bpm, we found that the 15-second window often contained too few samples. The 30-second window maximized both samples per window and number of windows. Then, we converted each to a binary label: one if their respiratory rates were below 85% of their baseline respiratory rates (i.e. breathing slowly and closer to their target respiratory rate at 75%) and zero if they were not. Finally, we calculated the mean of the binary labels and converted the ratio to a percentage to quantify the proportion of time spent breathing slowly relative to the baseline.

*Heart Rate Variability (HRV).* Heart rate variability, or the variation between consecutive heartbeats, was measured using the Polar H10 heart rate monitor, which records electrocardiograms (ECG) at a sampling rate of 130Hz. Participants wore the Polar sensor in the middle of their chest, touching their skin throughout the study. From the ECG signal, we extracted the root mean square of the interval between consecutive heartbeats (RMSSD) [50].

While HRV is linked to responses to stress [22], it's an over-simplification to interpret high HRV (i.e., high RMSSD) as lower stress and low HRV (i.e., low RMSSD) as higher stress. Rather, HRV should be read as the dynamic interaction of the parasympathetic branch and the sympathetic branches of the autonomic system [50]. We interpret HRV as an indicator of the activation of parasympathetic activity. We also recognize that because the experiment required participants to focus on cognitive tasks, the parasympathetic system may not be activated to a measurable state even if the participants breathe with the airflow guide.

### 4.3.2 Psychological Measures.

*State Anxiety.* The six-item short form of the State-Trait Anxiety Inventory (STAI-6; [32]) is a validated self-report questionnaire that measures state-level anxiety (e.g., "I am worried"). Participants provided their ratings on a 4-point scale ranging from (1) Not at all to (4) Very Much, with lower total scores indicate lower state anxiety.

*Positive and Negative Affect.* The Positive and Negative Affect Schedule (PANAS; [62]), comprising of 20 items, is a well-validated self-report measure of Positive Affect (PA; e.g. "Interested") and Negative Affect (NA; e.g., "Upset"). Participants rated their emotions using a 5-point scale ranging from 1 (*very slightly or not at all*) to 5 (*extremely*), where higher scores on each sub-scale (PA or NA) indicating higher intensity of the corresponding affect.

*Workload Using the Airflow-Guided Breathing Device.* The NASA Task Load Index (TLX; [17]) questionnaire consists of six single-question sub-scales that measure mental demand, physical demand, temporal demand, effort, frustration, and performance. Participants completed the scale after each of the two levels of memory task in the three experimental conditions (Figure 4) and rated their responses on a scale from 0 (*Very Low*) to 20 (*Very High*). The *performance* sub-scale's score was reversed and renamed as *reduced performance.* Considering temporal demand is not relevant to the current study (i.e., how fast participants were able to complete the cognitive task with or without the pulsing fan), this subscale was not included in the analyses. Thus, the total workload score was calculated by adding the five out of six subscale scores and ranged from 0 to 100.

### *4.3.3 Usage-Related Measures.*

*Self-reported Attention to and Adherence with the Airflow-Guided Breathing Fan.* After the pulsing airflow condition, participants rated their attention (i.e., "When you were playing the memory task, how often did you *pay attention to the fan?*") and their adherence to breathing with the device (i.e., "When you were playing the memory task, how often did you *breathe with the fan*?") on a 5-point scale: 1 (Never), 2 (Rarely), 3 (Sometimes), 4 (Very Often), and 5 (Always).

*User Experience and Device Usability.* At the end of the study, participants provided written feedback: on (1) their overall experience with the airflow-guided breathing device ("What was your experience like with the device? (e.g., What did you like or not like? Why?)"), (2) their perception of the pulsing air sensation during the memory task ("How did you feel about the air sensation from the fan while you were performing the memory tasks?"), and (3) the device's potential application in daily life ("Would you use this device in your daily life? If so, how?").

## 4.4 Procedures

After providing written informed consent, participants completed a demographic questionnaire and were randomly assigned to one of the six possible experimental condition orders described in Section 4.2. The study session was conducted in a quiet research study room with study personnel only.

*4.4.1 Baseline Phase.* In the Baseline phase, participants were instructed to watch a 5-minute nature video showing a forest and wildlife background while their respiration and heart rate data were continuously being captured (participants wore the Vernier Go Direct respiration belt and the Polar H10 heart rate monitor throughout the study session; detailed in Section 4.3.1). Afterward, participants completed the brief State Anxiety (STAI-6; [32]); and Positive and Negative Affect Schedule (PANAS; [62]) questionnaires and repeated the questionnaires after each study phase and the three experimental conditions. Participants' baseline respiratory rate was recorded and used to determine the fan's pulsing rate in the training phase and pulsing airflow condition.

*4.4.2 Training Phase.* Researchers enabled the intervention. Participants were asked to change the desk height, chair height, and angle of the laptop such that they felt the airflow around their nostrils. Participants were given verbal and written instructions with an illustration to synchronize their breathing with airflow cues from the fan for 5 minutes, inhaling when feeling a subtle air on their face and exhaling in its absence.

*4.4.3 Experiment Phase.* The three experimental conditions (no airflow, pulsing airflow, and constant airflow) varied by the airflow presence and pattern from the study fan. In the no airflow condition, the fan was off; in the constant airflow condition, it released continuous airflow; and in the pulsing airflow condition, it emitted subtle airflow that "pulsed" at 75% of each participant's baseline respiratory rate.

*4.4.4 Artificial Cognitive Loading Using the N-Back Task.* To examine whether users can breathe with the pulsing airflow even when engaging in primary tasks requiring different cognitive capacities, we administered two different levels of the N-Back task (i.e., 1-Back (easy) and 3-Back (hard); see Figure 7) in the three experimental conditions. The N-back task is a working memory task that requires participants to track a series of letters and identify when the current letter matches the one presented "N" steps earlier. The 1- and 3-Back tasks were selected to ensure a noticeable difference in the primary task difficulty.

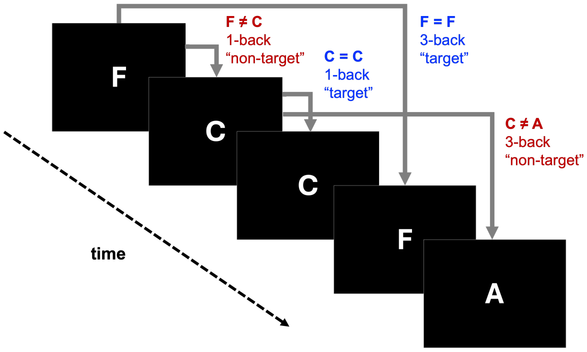

Fig. 7. In the three experimental conditions, participants engaged in a primary working memory task with two difficulty levels: 1-Back (easy) and 3-Back (hard). In the 1-Back task, participants were required to identify whether the letter presented in the current trial was presented *one* trial before the current trial and, thus, considered as an easy task. In the 3-Back task, participants determined whether the current letter was presented *three* trials earlier and, thus, considered a "hard" task. The 1- and 3-Back tasks were selected to ensure a noticeable difference in the primary task difficulty. Participants were instructed to press key 1 for "target" letters (i.e., if the current letter matches the letter presented "N" steps earlier; illustrated in blue) and 2 for "non-target" letters (i.e., if the current letter *does not* matches the letter presented "N" steps earlier; illustrated in red). They were allotted 2 seconds to respond, with any missed responses being recorded as incorrect.

After each task level, participants completed the workload questionnaire (NASA-TLX; [17]) regarding workload associated with playing the memory task (no airflow) and breathing with the fan (pulsing and constant airflow).

*4.4.5 Post-Experiment Phase.* Finally, participants were asked to provide written qualitative feedback about their experience using and perception of the airflow breathing guide as detailed in Section 4.3.3.

## 4.5 Statistical Analyses

Hierarchical linear mixed effects (LMEs) model was used to conduct primary and exploratory analyses on the study's quantitative measures using the *lme4* package [3] in R [46]. LME models were chosen as they account for both fixed effects (e.g., task difficulty and airflow condition) and random effects (e.g., individual differences) that allow for a robust analysis of repeated measures data with nested or hierarchical structures (e.g., participants experienced all experimental conditions). The primary analyses directly answered the research questions and were determined before the experiment, whereas the exploratory analyses were determined post-hoc to investigate the nuance of findings. We constructed the best-fitting LMEs by first constructing the initial model testing the main effect of experimental conditions with participants as a random effect to account for natural, individual differences on measures tested in each model. Then, we gradually constructed nested models by adding the main or interaction terms of a primary or exploratory variable. We chose the best-fitting nested model by comparing the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC). We chose one LME for each measure: each measure may have a different set of fixed effects, depending on which fixed effects produce best-fitting models (detailed in Appendix B).

### *4.5.1 Primary Analyses.*

*Effects of Airflow Conditions and Primary Task Difficulty on Breathing and Relaxation.* We used linear mixed-effects models (LMEs) to understand the effect of airflow conditions on (1) respiratory rate, (2) breathing amplitude, (3) HRV, (4) workload, (5) state anxiety, (6) negative affect, and (7) positive affect. We tested the main and interaction effects of **experimental conditions** (no airflow, constant airflow, and pulsing airflow; no airflow as the reference level) and **task difficulty** (easy and hard; easy as the reference level) on these measures to evaluate the individual and combined influence of these two variables. However, the effect of the cognitive task difficulty was not examined on state anxiety, negative affect, and positive affect as they were not administered after each cognitive task level. Additionally, as we anticipated the effect of time on these measures, we also tested the effect of **experimental blocks** (blocks 1, 2, 3) on all dependent variables.

#### 4.5.2 Exploratory Analyses.

*Effect of Pulsing Airflow on Slow and Deep Breathing.* We were further interested in whether the effect of pulsing airflow on slow breathing, as measured by the respiratory rate, and deep breathing, as measured by breathing amplitude, were different when participants were engaging in the easy or hard task. To conduct this analysis, we constructed LMEs on a subset of data: respiratory rate and breathing amplitude during baseline and training, as well as the no airflow and pulsing airflow conditions during the easy and hard cognitive tasks. By excluding the constant airflow condition and including the no-task conditions (i.e., baseline and training), we constructed the $3 \times 2$ effect of **task difficulty** (training as no task, easy task, and hard task) × **pulsing airflow** (no airflow and pulsing airflow): no airflow-no task (baseline phase), no airflow-easy task, no airflow-hard task, pulsing airflow-no task (training phase), pulsing airflow-easy task, and pulsing airflow-hard task.

*Correlation Between Actual and Target Respiratory Rate Stratified by Task Difficulty.* To understand how well participants breathed with the airflow guide, we tested the correlation between the actual and the target respiratory rate during training, as well as easy and hard cognitive tasks within the pulsing airflow condition using Spearman's correlation.

*Effects of Attention and Task Difficulty on Adherence to the Airflow Breathing Guide.* To understand the impact of different levels of attention on adherence to the pulsing airflow guide, we used LMEs to test the main effect of attention levels on (1) percentage of time spent in slow breathing and (2) percentage deviation from the target respiratory rate (i.e., the absolute error between target and actual respiratory rate). Participants were categorized into "low attention" (ratings of 1-2 out of 5, n = 11) and "high attention" groups (ratings of 3-4, n = 12) based on their self-reported attention to the breathing guide.

*Effect of Airflow Conditions on Cognitive Task Performance.* Although participants' performance on the cognitive task was not an a priori interest, we conducted an exploratory analysis on the effect of using the airflow breathing guide on participants' behavioral performance on the easy and hard cognitive tasks in the three experimental conditions.

### 4.6 Qualitative Analysis

We conducted qualitative analysis to assess participants' experience using and perception of the airflow guided breathing device. Responses from all participants with valid survey data (N=30) from the three open-ended, post-experiment questions were analyzed by the co-first authors using a thematic analysis approach [6]. Each researcher independently generated codes/labels for each participant's responses. The co-first authors then discussed and iteratively consolidated these codes. The second co-first author then organized the consolidated codes into clusters of lower-level themes that were descriptive of the responses. The first and third co-first authors reviewed and validated these themes. The final codebook, mapping these lower-level themes to the final codes, is included in Appendix A. These lower-level themes were then developed into higher-level themes, which were reviewed and validated by the first and third co-first authors, and reported in Appendix A. Participants' quotes have been de-identified to maintain anonymity and edited for brevity.

## 5 RESULTS

Our research revealed that pulsing airflow effectively promotes slow breathing during easy cognitive tasks, but its impact diminishes during more challenging tasks. Participants' respiratory rates generally aligned with their target rates across all conditions, but they maintained slow breathing the longest – over 40% of the time – during easier tasks. Interestingly, the pulsing guide required minimal attention, as even those with low self-reported attention spent about 25% of their task time in slow breathing. Although using the airflow guide increased workload and did not significantly impact stress levels physiologically or psychologically, it was effective in reducing breathing rate and promoting mindfulness.

### 5.1 Users Can Breathe With The Airflow Guide While Engaging in A Primary Task

*5.1.1 Pulsing Airflow Elicited Slower Breathing in Training and Easy Task.* The best-fitting LME model showed that participants' breathing rates were significantly lower in the pulsing airflow condition compared to the no airflow condition ($\beta = -1.86, 95\%CI = [-2.55, -1.17], p < 0.001$). Adding task difficulty to the model significantly improved the model fit ($\chi^2 = 6.60, p = 0.010$), while the experimental conditions × task difficulty effect and the effect of block did not ($p = 0.228$ and $p = 0.860$, respectively). The main effect of task difficulty indicated that participants' respiratory rates were significantly lower on average in the easier (1-Back) compared to the harder (3-Back) primary task ($\beta = 0.73, 95\%CI = [0.17, 1.29], p = 0.011$).

Further post-hoc pairwise comparisons with Bonferroni correction indicated that on average across task difficulty levels, participants' respiratory rates were significantly lower in the pulsing airflow condition compared to the constant ($\Delta M = 2.07, t = 5.96, p < 0.001$) and no airflow ($\Delta M = 1.86, t = 5.25, p < 0.001$) conditions (Figure 8a); the latter two did not differ significantly (p > 0.999). These findings indicate that constant airflow did not result in a slower respiratory rate, underscoring that the reduction in respiratory rate is specifically attributable to the unique effect of pulsing airflow, rather than to airflow in general.

Based on these findings, we conducted an exploratory investigation to determine whether the pulsing airflow's effect in slowing respiratory rates differed when participants focused solely on breathing with the pulsing airflow guide, without engaging in additional cognitive tasks (i.e., during training). Specifically, we assessed the effect of airflow condition (no airflow vs. pulsing airflow, excluding constant airflow) and task difficulty (no cognitive task, easy task, and hard task) using a 2 × 3 factorial design. In this design, the "no airflow-no task" condition corresponds to breathing rate data from the Baseline Phase, while the "pulsing airflow-no task" condition corresponds to data from the Training Phase.

We found a main effect of airflow condition, ($\beta = -4.04, 95\%CI = [-5.30, -2.78], p < 0.001$), suggesting that on average across no task and easy and hard tasks, respiratory rates were significantly lower in the pulsing than the no airflow condition (Figure 9a). There was also a main effect of task difficulty, suggesting that on average across pulsing and no airflow conditions, the harder primary task was associated with a significantly higher respiratory rate than the no task condition ($\beta = 1.45, 95\%CI = [0.19, 2.71], p = 0.025$), while the easier task was not ($p = 0.070$). We also found a significant interaction between the pulsing airflow condition and the hard task ($\beta = 2.74, 95\%CI = [0.95, 4.52], p = 0.003$), but not between pulsing airflow and the easy task (p = 0.074), which suggest that the more demanding cognitive task (3-Back task) was associated with a significantly higher respiratory rate, potentially due to increased cognitive load or stress, diminishing the pulsing airflow's effect in slowing down respiratory rate.

Post-hoc pair-wise comparisons revealed that participants' respiratory rates were significantly higher in the no airflow compared to the pulsing airflow condition within the no task $\Delta M = 4.04, t = 6.34, p < 0.001$) and easy task conditions ($\Delta M = 2.41, t = 6.34, p < 0.001$). However, this statistically significant difference was not evident in the hard (3-Back) task ($p = 0.390$; Figure 9a). Furthermore, we found that participants were breathing significantly slower using the pulsing airflow guide when they did not have any other cognitive task compared

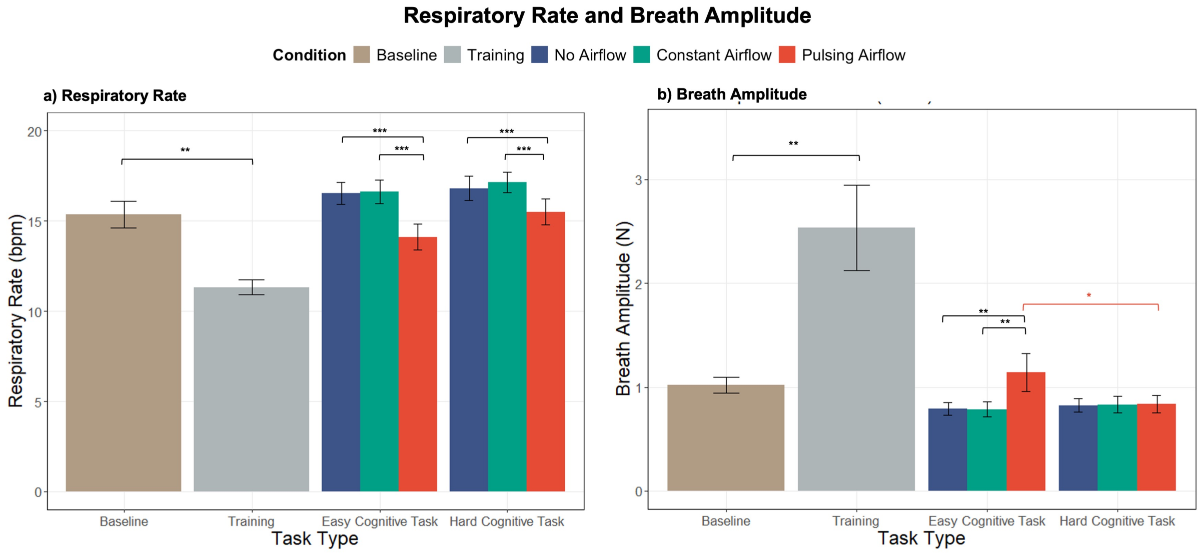

Fig. 8. Participants' (a) respiratory rate (a) and breath amplitude in condition (baseline, training, no airflow, constant airflow, and pulsing airflow) and task difficulty (easy and hard). *p<0.05; **p<0.01; ***p<0.001. Error bars indicate SE.

to when they played the easy ($\Delta M = -2.79, t = -4.38, p < 0.001$) and hard ($\Delta M = -4.19, t = -6.57, p < 0.001$) cognitive tasks. However, there was no statistically significant difference in breathing rate between the easy and hard tasks.

Our primary and exploratory analyses indicate that the pulsing airflow has a slowing effect on respiratory rate. While this effect is most pronounced when users are not engaged in other cognitive tasks, our findings demonstrate that pulsing airflow can still effectively reduce respiratory rate during easy cognitive tasks, though its effectiveness diminishes as the cognitive demands of the task increase. Complementing this, our qualitative analysis shows that participants are more willing to use the pulsing airflow guide during shallow work or tasks that are not cognitively demanding (see Appendix A; "usage context" row), such as "organizing calendars" (P09), "answering emails, completing spreadsheets, [and] other repetitive tasks" (P27). Together, these findings suggest that pulsing airflow is particularly suited for low-demand cognitive environments where it can be an effective tool for modulating breathing.

### 5.1.2 *Pulsing Airflow Elicited Deeper Breathing in the Training Phase, but Not in Easy or Hard Tasks.*

We were also interested in examining whether participants were breathing more deeply as a result of using the pulsing airflow guide. Thus, we conducted primary analyses on breath amplitude similar to those for respiratory rate (Sections 4.5.1 and 4.5.2).

The best-fitting LME model revealed a significant main effect of airflow condition on breath amplitude (Figure 8b). Specifically, pulsing airflow resulted in significantly higher breath amplitude (i.e., deep breathing) compared to no airflow ($\beta = 0.35, 95\%CI = [0.17, 0.35], p < 0.001$) while constant airflow did not have a significant impact on breath amplitude ($p = 0.964$). The main effect of task difficulty ($p = 0.738$) was not statistically significant, suggesting that breath amplitude did not significantly differ between the easy and hard tasks. However, we found a significant interaction between airflow conditions and task difficulty ($\beta = -0.34, 95\%CI = [-0.59, -0.08], p = 0.011$), indicating that the effect of pulsing airflow on breath amplitude

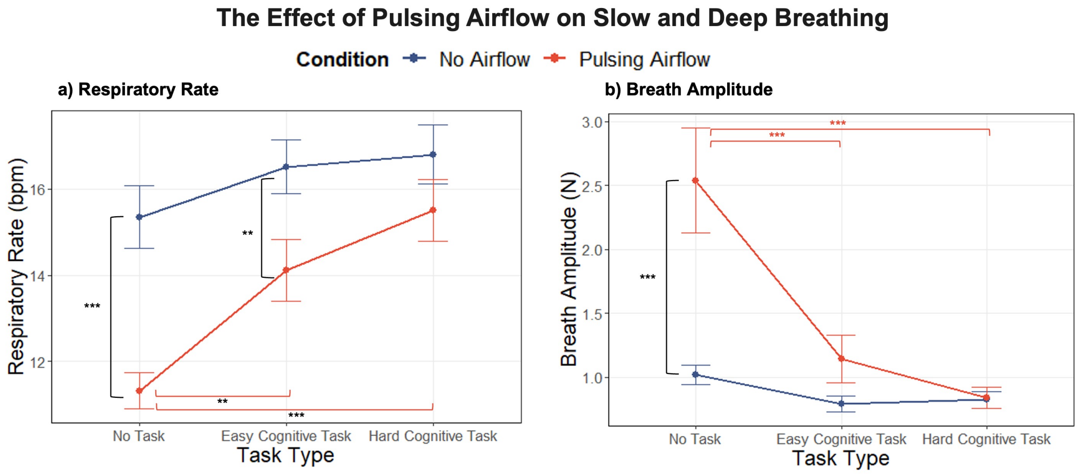

Fig. 9. The interaction of pulsing airflow and task difficulty (easy and hard) on respiratory rate (a) and breath amplitude (b). **p<0.01; ***p<0.001. Error bars indicate SE.

decreased as task difficulty increased. This interaction effect improved model fit ($\chi^2 = 11.14, p = 0.011$), and experimental blocks did not ($p = 0.585$).

Post-hoc pairwise comparisons revealed that, within the easy task, participants exhibited significantly higher breath amplitude in the pulsing airflow condition compared to no airflow ($\Delta M = -0.35, t = -3.79, p = 0.002$) and constant airflow ($\Delta M = -0.35, t = -3.85, p = 0.002$) conditions (Figure 8b). There were no significant differences between the constant and no airflow conditions in either the easy (1-Back) or hard (3-Back) tasks ($ps > 0.999$), nor between any conditions in the hard task ($ps > 0.999$). Additionally, within the pulsing airflow condition, participant breath amplitude was significantly higher in the easier compared to the harder task ($\Delta M = 0.30, t = 3.29, p = 0.012$). These results suggest that pulsing airflow effectively promotes deeper breathing during easier, less cognitively demanding tasks, but not during more challenging tasks, and that this effect is specifically attributable to its unique characteristics (i.e., pulsing), rather than to airflow in general (e.g., constant airflow).

Motivated by these findings, we carried out exploratory analyses to determine whether the effect of pulsing airflow on deep breathing increases when participants concentrated solely on breathing with the pulsing airflow guide, without additional cognitive tasks. We used a 2 × 3 factorial design identical to the one used in exploratory analysis in Section 5.1.1.

Confirming the previous finding, the pulsing airflow was associated with significantly higher breath amplitude compared to the no airflow condition ($\beta = 1.52, 95\%CI = [1.07, 1.97], p < 0.001$). However, on average across the no airflow and pulsing airflow conditions, breath amplitudes during the easy ($p = 0.319$) and hard ($p = 0.389$) tasks were not significantly different from the no-task condition, indicating that having no primary task does not increase breath amplitude. However, the interactions between the pulsing airflow and both the easy ($\beta = -1.17, 95\%CI = [-1.80, -0.53], p < 0.001$) and the hard task ($\beta = -1.50, 95\%CI = [-2.14, -0.86], p < 0.001$) were significant, suggesting that the effect of pulsing airflow was largest in the no-task condition and decreased in the easy and hard tasks (Figure 9b). Post-hoc pair-wise comparisons indicated that breath amplitude was significantly higher in the pulsing compared to no airflow when participants had no primary cognitive task ($\Delta M = -1.51, t = -6.657, p < 0.001$). However this effect was not observed during easy or hard tasks ($ps > 0.999$)

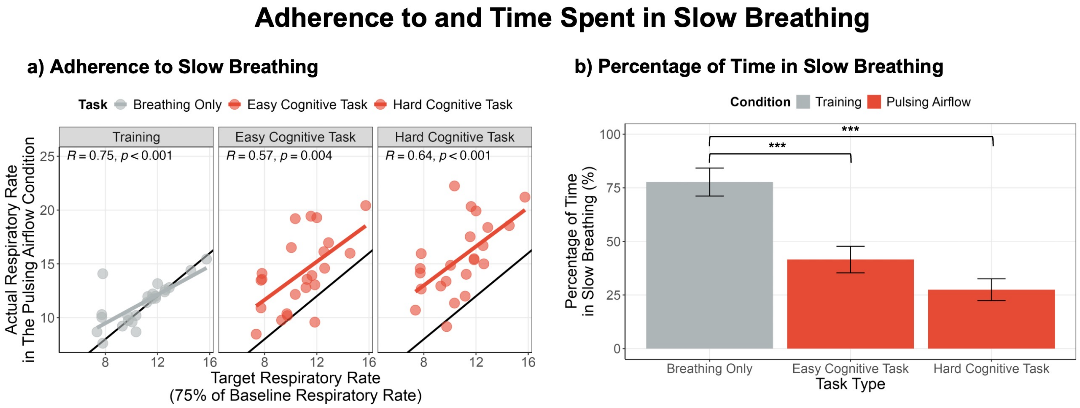

Fig. 10. Adherence to the target respiratory rate (a) and time spent in slow breathing (b) with pulsing airflow during no cognitive task, easy cognitive task, and hard cognitive task.

(Figure 9b), indicating that participants breathed more deeply with pulsing airflow only when not engaged in a cognitive task. Within the pulsing airflow condition, breath amplitude was similar between easy and hard tasks ($p > 0.999$), but significantly lower during both easy ($\Delta M = 1.39, t = 6.12, p < 0.001$) and hard $\Delta M = 1.70, t = 7.46, p < 0.001$) tasks compared to the no-task condition, suggesting shallower breathing when cognitive tasks were introduced.

Together, our primary and exploratory findings suggest that while pulsing airflow effectively promotes deeper breathing in the absence of cognitive demands, its impact diminishes when participants are engaged in tasks that require mental effort.

*5.1.3 Users Were Able to Synchronize Breathing and Maintain Slow Breathing.* To examine how well participants breathed with the pulsing airflow under different cognitive tasks, we conducted exploratory analyses of the correlation between participants' respiratory rates and target slow breathing rates and percentage of time spent in slow breathing during training phase, easy, and hard tasks (detailed in Section 4.5.2). Spearman's correlation showed strong positive correlations during training ($R = 0.75, p < 0.001$), and both easy ($R = 0.57, p = 0.004$) and hard tasks ($R = 0.64, p < 0.001$) confirming participants' ability to match the target respiratory rate across tasks (Figure 10a). Participants maintained slow breathing (below 85% of baseline) approximately 70% of the time during training, over 40% during easy tasks, and more than 20% during hard tasks (Figure 10b). Task type (breathing only, easy task, hard task) significantly impacted slow breathing duration, with easy ($\beta = -36.15, 95\%CI = [-49.12, -23.18], p < 0.001$) and hard tasks ($\beta = -50.21, 95\%CI = [-63.18, -37.24], p < 0.001$) leading to less time in slow breathing compared to breathing only (no cognitive task). Post-hoc comparisons indicated participants spent about 36% less time in slow breathing during easy tasks ($\Delta M = 36.2, t = 5.57, p < 0.001$) and 50% less during hard tasks ($\Delta M = 50.2, t = 7.73, p < 0.001$) relative to breathing-only condition, with no significant difference between easy and hard tasks ($p = 0.107$). These results suggest participants could follow the breathing guide with and without a cognitive task, but time spent in slow breathing decreased as task difficulty increased.

Our qualitative analysis sheds light on these findings, revealing that participants experienced a learning curve when adjusting their breathing to the guide. Initially, they faced challenges synchronizing their breathing with the airflow guide while engaging in the primary task (the N-Back tasks) but gradually became attuned to the pulsing airflow. As P24 stated, "The device makes it complicated to complete the task at first. However, once used to it, it was quite OK."

#### 5.1.4 *Higher Attention Increased Adherence to Airflow Guide.*

Lastly, we further explored how attention levels affected adherence to the pulsing airflow guide during easy and hard tasks as measured by (1) percentage deviation from the target respiratory rate (i.e., absolute error with the actual respiratory rate; Figure 11a) and (2) percentage of time spent in slow breathing (Figure 11b).

Our analyses revealed that attention levels significantly impacted percentage deviation from target respiratory rate ($\beta = -36.53, 95\%CI = [-56.28, -16.78], p = 0.001$) with no significant main effect of task level ($p = 0.105$) or attention × task difficulty interaction effect ($p = 0.509$). Additionally, attention levels significantly impacted the percentage of time in slow breathing ($\beta = 37.00, 95\%CI = [17.92, 56.04], p < 0.001$) with no effect of task difficulty ($p = 0.324$) or attention × task difficulty interaction ($p = 0.193$). These results demonstrated that higher attention levels significantly increased users' ability to sync their breathing with the target respiratory rate, as reflected by significantly lower deviations from target breathing rate (Figure 11a), and to maintain slow breathing, as reflected by significantly higher percentage of time in slow breathing (Figure 11b); this effect was uniform across task difficulty levels.

In short, results from Sections 5.1.3 and 5.1.4 demonstrate that, while participants' actual breathing rates closely matched their target rates across the training phase, easy, and hard tasks, participants maintained slow breathing for the longest – over 40% of the time – in the easy cognitive task, and their adherence and ability to maintain slow breathing, regardless of task difficulty, increases with higher levels of attention.

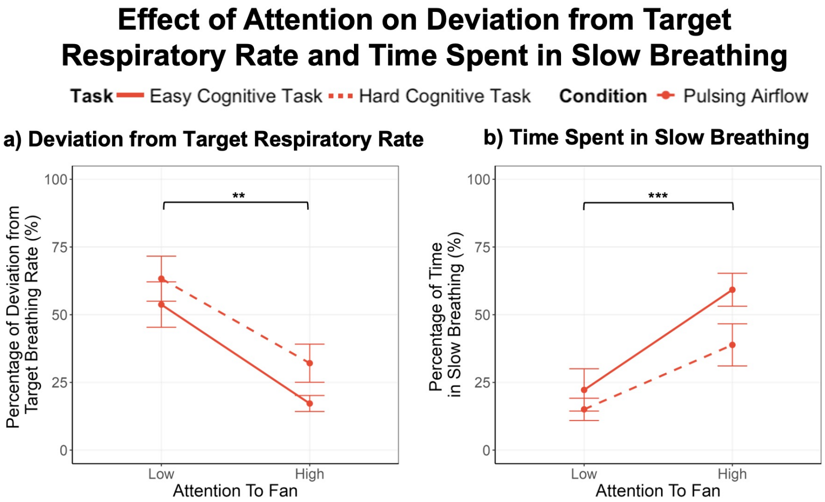

Fig. 11. Effect of attention (low and high) on deviation from target respiratory rate (a) and time spent in slow breathing (b). **p<0.01; ***p<0.001. Error bars indicate SE.

## 5.2 Breathing With the Airflow Guide Increased Overall Workload, Physical Demand, and Perceived Decline in Performance

To investigate how pulsing airflow affects perceived workload, we assessed the impact of three airflow conditions on the five NASA-TLX subscales (mental demand, physical demand, effort, frustration, and reduced performance) and overall workload score. We also tested the influence of task difficulty and its interaction with airflow conditions to determine if the effect of airflow conditions on workload varies by task complexity.

As anticipated, we found a significant main effect of task difficulty on mental demand ($\beta = 5.26, 95\%CI = [4.08, 6.44], p < 0.001$; Figure 12a), effort ($\beta = 3.75, 95\%CI = [2.63, 4.89] p < 0.001$; Figure 12b), frustration ($\beta = 3.00, 95\%CI = [1.84, 4.16], p < 0.001$; Figure 12c), physical demand ($\beta = 1.68, 95\%CI = [0.64, 2.73], p = 0.002$; Figure 12d), and perceived reduced performance ($\beta = 4.68, 95\%CI = [3.47, 5.89], p < 0.001$; Figure 12e), as well as the total workload ($\beta = 20.71, 95\%CI = [16.05, 25.37], p < 0.001$; Figure 12f). These findings suggest that greater task difficulty is associated with a significant increase in perceived mental demand, effort, physical demand, frustration, and reduced performance as well as total workload.

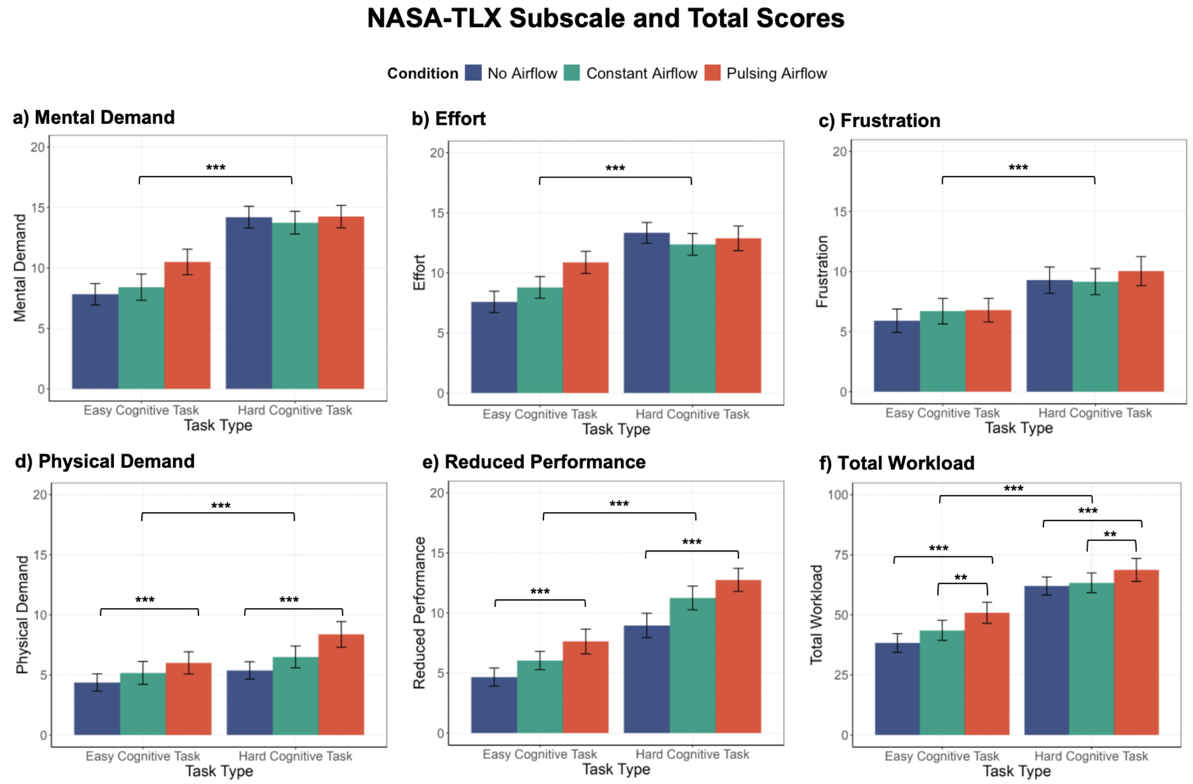

Fig. 12. Participants' perceived (a) total workload, (b) mental demand, (c) effort, (d) physical demand, (e) frustration, and (f) reduced performance in the easy and hard cognitive tasks in the no airflow, constant, and pulsing airflow conditions. $^{**}$p<0.01; $^{***}$p<0.001. Error bars indicate SE.

Our analyses also revealed a significant effect of experimental conditions on all subscales, except frustration and total workload (mental demand: $\textit{constant}\ \beta = 0.24, 95\%CI = [-1.20, 1.69], p = 0.738$, $\textit{pulsing}\ \beta = 1.55, 95\%CI = [0.10, 3.00], p = 0.036$, effort: $\textit{constant}\ \beta = 0.19, 95\%CI = [-1.21, 1.58], p = 0.792$, $\textit{pulsing}\ \beta = 1.62, 95\%CI = [0.23, 3.01], p = 0.023$); physical demand: $\textit{constant}\ \beta = 1.15, 95\%CI = [-0.13, 2.43], p = 0.077$, $\textit{pulsing}\ \beta = 2.52, 95\%CI = [1.24, 3.80], p < 0.001$; reduced performance: $\textit{constant}\ \beta = 1.82, 95\%CI = [0.33, 3.30], p = 0.017$, $\textit{pulsing}\ \beta = 3.56, 95\%CI = [2.07, 5.04], p < 0.001$; total workload: $\textit{constant}\ \beta = 3.06, 95\%CI = [-2.66, 8.78], p = 0.292$; $\textit{pulsing}\ \beta = 10.36, 95\%CI = [4.64, 16.08], p < 0.001$; frustration: $\textit{constant}\ p = 0.830$, $\textit{pulsing}\ p = 0.241$). However, our follow-up pairwise comparisons using Bonferroni correction showed that the effect of airflow condition on these measures was only maintained in the total workload, physical demand, and perceived reduced performance subscales, but not the mental demand and effort subscales ($ps > 0.05$). Specifically, our post-hoc analyses showed that, compared to the no airflow condition, the pulsing airflow condition was associated with significantly higher levels of total workload ($\Delta M = -10.36, t = -3.58, p = 0.002$; Figure 12f), physical demand ($\Delta M = -2.52, t = -3.90, p < 0.001$; Figure 12d), and perceived decline in performance ($\Delta M = -3.56, t = -4.74, p < 0.001$; Figure 12e). Total workload was also significantly higher in the pulsing relative to the constant airflow condition ($\Delta M = -7.30, t = -2.53, p < 0.038$; Figure 12f). In contrast, participants' total workload (Figure 12f), physical demand (Figure 12d), and perceived reduced performance (Figure 12e) did not significantly differ between the constant and pulsing conditions and between the constant and no airflow conditions ($ps > 0.05$). Adding the task difficulty × airflow conditions interaction term did not significantly improve model fit $ps > 0.05$), nor was the interaction effect statistically significant for any measure ($ps > 0.05$). Although not of primary interest, we tested the main effect of experimental block in our models, reported in Appendix B.2).

These findings suggest that the pulsing airflow significantly increased physical workload (Figure 12d), perceived decline in performance (Figure 12e), and overall workload (Figure 12f) but had no significant effect on mental demand, effort, and frustration. However, our qualitative analysis revealed that some participants found breathing with the fan cognitively effortful and it occasionally distracted them from the main task (e.g., "I found myself thinking about it while trying to remember the letters" (P28)). These results demonstrate that pulsing airflow primarily increases physical and overall workload, as well as perceived decline in performance, while inducing minimal cognitive challenge for participants.

### 5.3 Breathing with the Airflow Guide Did Not Lead To Relaxation but Promoted Mindfulness

We evaluated the effect of airflow conditions on relaxation as measured in state anxiety, negative affect, and positive affect, as well as HRV (reported in RMSSD; detailed in Section 4.5.1).

Our analyses revealed no significant main effects of airflow conditions on state anxiety (*constant* $p = 0.237$; *pulsing* $p = 0.980$), positive affect (*constant* $p = 0.381$, *pulsing* $p = 0.892$), and negative affect (*constant* $p = 0.424$, *pulsing* $p = 0.904$, ), suggesting that the pulsing condition did not induce relaxation. However, our exploratory analyses showed significant main effect of experimental blocks (i.e., block 1, 2, 3) on anxiety and negative affect, but not positive affect (further statistical details in Appendix B.1). Follow-up pairwise comparisons indicated that, across task difficulty and conditions, participants reported higher state anxiety in block 1 relative to block 3 ($\Delta M = 1.95, t = 3.08, p < 0.012$; Figure 13a), and higher negative affect in block 1 relative to block 2 ($\Delta M = 3.08, t = 4.20, p < 0.001$) and block 3 ($\Delta M = 4.01, t = 5.39, p < 0.001$; Figure 13d).

In addition, we found a significant main effect of airflow conditions on RMSSD ($constant\ \beta = -5.66, 95\%CI = [-10.68, -0.65], p = 0.027$, $pulsing\ \beta = -3.37, 95\%CI = [-8.39, 1.64], p = 0.186$), but further post-hoc pairwise analyses showed no significant differences on RMSSD between no airflow and constant airflow ($p = 0.082$), no airflow and pulsing airflow ($p = 0.560$), or constant airflow and pulsing airflow ($p > 0.999$). These results show that, overall, participants' self-reported anxiety and negative affect decreased as the study progressed, but neither the pulsing airflow nor the task difficulty significantly affected participants' relaxation.

Despite the lack of statistically significant effects on physiological and psychological relaxation measures, our qualitative analysis revealed that the pulsing airflow fostered greater mindfulness by increasing participants' awareness of their thoughts and bodily sensations. For example, participants stated that the pulsing airflow "helped them to focus/inhale better" (P31) and "was a good reminder to not let [their] mind wander too much" (P06). Others also highlighted that the device served as an unobtrusive reminder to regulate their breathing, particularly when engaging in challenging cognitive tasks. P09 said, "[When I was] doing the hard [cognitive task] I did notice that I was holding my breath a lot more and the fan reminded me to stop doing that" and P15 reaffirmed that the pulsing airflow “felt like it was encouraging [them] to do something that was good for me (i.e., breathe better and deeper because I often forget to breathe).”

Additionally, others highlighted that the pulsing airflow induces more positive emotion when engaging in the primary task. Specifically, participants reported that the pulsing airflow was “very soothing” (P07) and made them “feel less stress[ed]” (P04). P14 also said, “The system encouraged me to breathe because I am a shallow breather and hold my breath too often when I am concentrating.” However, some participants did report more positive emotions when using the continuous rather than the pulsing airflow. For example, P29 stated that they were “calmer when [the fan was] continuously on. The on/off situation [was] quite stressful.”

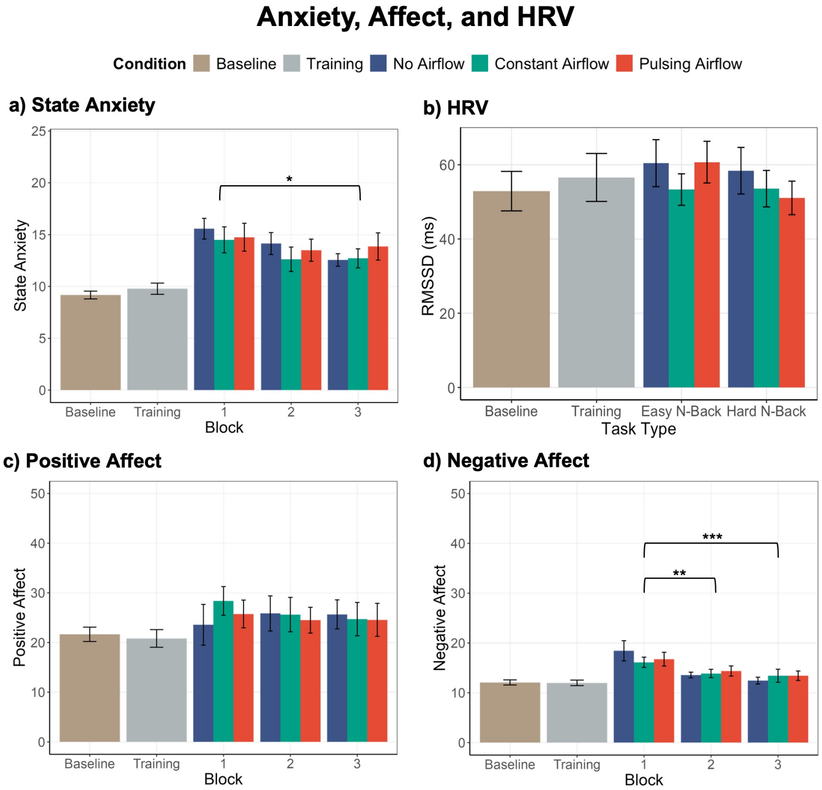

Fig. 13. Participants’ (a) state anxiety, (b) HRV, (c) positive affect, (d) negative affect as a function of in block (for state anxiety, positive affect, and negative affect) and in task type (for HRV), as well as in the no airflow, constant airflow, and pulsing airflow conditions.

## 5.4 Breathing With the Airflow Guide Did Not Adversely Affect Cognitive Task Performance

We used LME to examine the effects of pulsing airflow and task difficulty on participant performance in the easy and hard cognitive tasks in terms of percentage accuracy. We found a significant main effect of task difficulty ($\beta = -5.25, CI[-5.96, -4.54], p < 0.001$), indicating that higher task difficulty was associated with significantly lower percentage accuracy, and a significant main effect of airflow conditions: on average, compared to the no airflow condition, the pulsing airflow is associated with significantly lower performance accuracy

($\beta = -1.91, CI[-3.64, -0.19], p = .030$) while the constant airflow did not ($p = 0.105$). However, post-hoc pairwise comparisons indicated no significant differences in task accuracy among the three experimental conditions. Adding the experimental condition × task difficulty interaction effect did not improve the model fit ($\chi^2 = 0.28, p = 0.870$). Taken together, these results indicated using the pulsing airflow guide did not adversely affect participants' performance in the cognitive tasks (Figure 14).

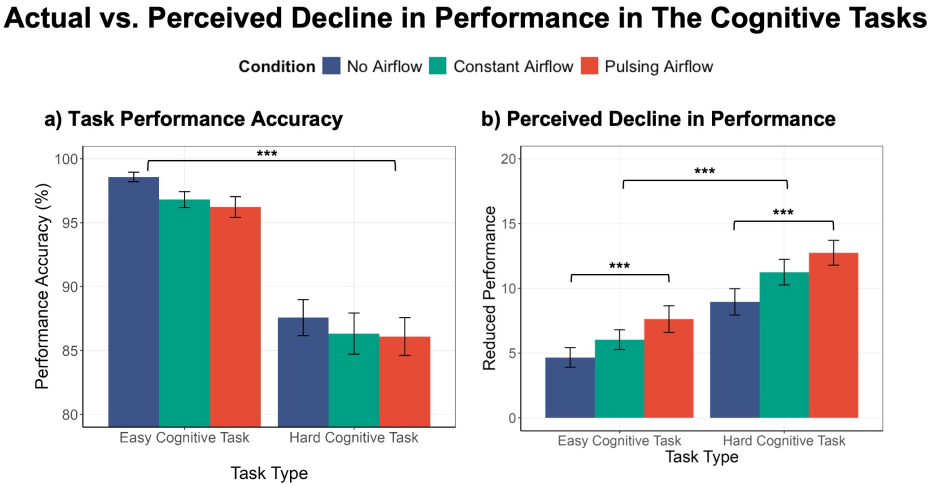

Fig. 14. Participants' (a) actual and (b) perceived performance in the easy and hard cognitive tasks in the no airflow, constant, and pulsing airflow conditions. Participants accurately perceived their performance decreased easy and hard tasks across conditions. However, while participants perceived significantly worse performance in the pulsing than in the no airflow condition, their actual performance did not significantly differ between the three conditions. **p<0.01; ***p<0.001. Error bars indicate SE.

## 6 DISCUSSION

In this study, we evaluated BreathePulse, a peripheral breathing guide that uses subtle, pulsing airflow as a stress intervention for information work and assessed its feasibility, workload, and impact on relaxation. The qualitative evaluation offered additional nuance on cognitive resources, learning curves, and benefits associated with breathing with the airflow guide, as well as considerations for future peripheral breathing intervention devices. In the following section, we (1) discuss how effective airflow breathing guide is in relationship with other modalities and (2) discuss the relationship between salience and attention while providing guidelines on designing guides that consider workload and attention as a resource.

### 6.1 How Effective is Breathing with Implicit Airflow Cues

Participants breathed slower, matched their respiratory rate with the airflow guide, and sustained slow breathing across task contexts (no task, easy task, and hard task). This answers our RQ1 – *participants can breathe with an implicit airflow guide while performing primary tasks.* However, the airflow guide's effect on respiratory rate decreases as the primary task's cognitive demand increases. Compared to prior work, implicit airflow outperformed some studies in overall respiratory rate reduction and adherence to guide. The respiratory rate was reduced by 2.41bpm during the easy task, greater than Morajevi et al.'s 1.8bpm reduction [40], but less than Tabor et al.'s 4.8bpm reduction [57]. Choi et al. observed that one participant matched the target breathing rate for a short duration (less than two minutes) without further group-level information [9]. Our results for time on target rate – the percentage of time in slow breathing – are 41.5% for the easy task and 27.5% for the hard task. Thus, the time on target during the easy task was better than Tabor et al.'s average of 28% across five modalities. Even during the stricter hard task, BreathePulse's adherence outperforms Tabor et al.'s brightness and haptic cues.

In addition, we found that total workload increased when participants needed to follow the airflow guide (RQ2), driven by the increase in physical demand and perceived reduced performance. The increased physical demand showcased that participants physically struggled to synchronize with the cues while occupied by the primary task. As for the perceived reduction in performance, it is important to note that the pulsing airflow did not affect the actual performance. This perception may be due to emotional bias, as the learning curve and frustration from attempting to synchronize their breathing with the pulsing airflow could have led to a negative self-assessment. Additionally, participants might have factored in how well they matched the airflow guide, rating their performance lower if they did not achieve perfect synchronization. Compared to prior work, our work provided the most detailed characterization of workload associated with using a peripheral breathing guide while performing primary tasks. The workload associated with AmbientBreath was not significantly different from having no intervention, but the context of AmbientBreath was driving rather than information work [24]. Choi et al. reported that their pneumatic guide did not significantly increase workload, but this finding lacked statistical support [9]. Due to the different contexts and unknown statistical metrics, it is infeasible to directly compare the workload of BreathePulse with the workload of related peripheral breathing guides.

Breathing with the airflow guide had no immediate effect on self-reported anxiety and affect, or physiological stress measured by HRV (RQ3). The relaxation benefits of traditional slow, deep breathing rely on deep breathing to activate the parasympathetic nervous system, while slow breathing is a way to achieve deep breathing [8]. Our findings align with this: participants breathed slowly but not deeply during the primary tasks, which may explain the lack of observed impact on relaxation. This result is reasonable since this study focused on the immediate effect of following the airflow guide; the experiment was short and intense, as the participants repeatedly performed intensive cognitive tasks without the opportunity for relaxation. In addition, our observations were aligned with prior work that utilized N-Back to test the effect of guided breathing [9]. Similarly, several other peripheral breathing guides also observed minimal impact on stress and anxiety [1, 27]. Several studies have noted that short-term RMSSD is not altered even when deep, slow-guided breathing was performed as the main task without other cognitive tasks [30, 49].

In conclusion, compared to prior work, BreathePulse was highly effective at promoting slow breathing, with high adherence and prolonged time spent in slow breathing. The workload of this modality was significant, potentially due to the difficulty of perceiving the airflow guide during intense cognitive tasks. The varying contexts and lack of statistical clarity in prior studies make direct workload comparisons challenging. While BreathePulse's effect on stress was non-significant, it was comparable to other peripheral breathing guides.

## 6.2 Design with Consideration of Workload and Attention for Different Contexts

Ideally, breathing with a peripheral breathing guide would be implicit and require little workload: the user perceives the breathing guide through exogenous attention and follows the breathing guide without deliberation. In practice, the current design has yet to achieve this goal. Tabor et al. [57] found similar results, stating that "a degree of focused attention [on the breathing guide] will likely be required – especially in early use". While our study concurs with this finding, we believe that designing breathing guides while considering workload as a resource can help reduce the reliance on attention and design suitable interventions for different primary tasks.

Our study revealed the saliency of the breathing guide influenced the effect of guided breathing. A critical design choice of BreathePulse was the subtle airflow that was just perceivable so that the user could easily focus on the primary task, a design choice intended to reduce workload. However, this design choice led to unexpected consequences. Due to the subtlety of the airflow, participants reported it was hard to perceive it while focusing on the primary task. To compensate for the subtlety, we suspect that the participants allocated endogenous attention (i.e., attention that is top-down and voluntary) to perceive instead of the ideal case, which is to use exogenous attention (i.e., attention that is stimulus-driven and involuntary) to sense the cues [29]. As perceiving the breathing guide competed for endogenous attention with the primary task, following the breathing guide became more difficult as the primary task became harder.

In addition to perceiving the airflow guide, the user must follow the guide deliberately or implicitly. While it requires workload to follow the airflow guide accurately, we also discovered that a low level of attention also enables some effect in lowering the respiratory rate and prolonging the time spent in slow breathing. The transition from a deliberate, voluntary task to an implicit, involuntary task typically requires learning, as suggested by some participants noting that they gradually became better at following the breathing guide.

For designers, straightforward strategies to enable longer learning time include having a longer adaptation period or dedicated training time before deploying the intervention. More importantly, we invite designers to think about *how much workload and effect is sufficient for the use scenario*. In a realistic workplace, various factors contribute to the adaptation and effect of an intervention, most of which are irrelevant to the intervention itself (e.g., policy integration [41], time constraints [7, 41, 52], workspace environment [7]). Therefore, it's important to identify the target effect of the intervention. For instance, if the goal is to make a stress intervention available for an open-space workplace with little available time for intervention, it can be sufficient to use subtle airflow, little training, and expect the workers to only loosely follow the airflow guide during shallow tasks. Workers can choose when to allocate more attention to the airflow guide to receive more benefits and when to ignore it altogether. In contrast, for an intervention aiming to lower anxiety for high-intensity jobs, such as content filtering or answering emergency calls, the intervention needs to have a high adherence while not demanding high workload. Designers can consider integrating training to use the breathing guide into the onboarding sessions, ensuring that workers receive sufficient time to pass the learning curve and reduce the workload associated with following the breathing guide.

## 6.3 Limitations

### *6.3.1 Prompting Participants to Breathe.*

Although we intended to assess whether guided breathing can be implicit, the training session prompted the participants to deliberately and actively follow the airflow guide. Initially, we believed this to be necessary for learning how to follow the airflow guides; however, it also biased some participants to treat breathing with the fan as a deliberate task and to pay attention to it even during cognitive tasks. Some participants noted that the dual-task phenomenon caused additional stress since they attempted to do both deliberately. The deliberate attention may have affected the workload of following the airflow guide and completing the primary task.

### *6.3.2 Learning Curve and Habituation.*

The learning curve for using BreathePulse may have influenced participants' perception of difficulty and overall performance. To mitigate this and to achieve a more implicit interaction, participants may need to use the device for a more extended period such that the initial training or priming can be washed out and breathing with the fan becomes habitual.

### *6.3.3 Unintentional Auditory Cues.*

In qualitative feedback from the participants, some noted that they could both hear the fan noise and feel the airflow cue. The feedback on the multi-modal cues was mixed: some participants found the sound of the fan to be a helpful additional cue, while others found it noisy and distracting.

## 6.4 Future Work

*6.4.1 Wearable and Infrastructural Airflow Guidance.* Airflow is fascinating as a medium for breathing guidance because it can be integrated as a ubiquitous computing system at several levels: as a wearable, as a ubiquitous gadget as used in this study, or as an infrastructural intervention (e.g., by adding pulsation to airflow from the heating, ventilation, and air conditioning systems). Considering user feedback in this study about mobility, the wearable direction seems most promising. Other modalities of guided breathing systems have also moved towards a wearable form factor [10, 43], and there are existing devices that already deliver air as wearable, such as neck fans and some advanced face masks. Positioning the fan around the user in a wearable can also enhance the targeting of the airflow stream, enabling effective intervention delivery without sacrificing subtlety by increasing intensity. While likely less effective, infrastructural interventions remain an interesting future application due to their scalability and potential to intervene at a group or public health level.

*6.4.2 Long-Term in-the-Wild Evaluation with Higher Levels of Personalization.* In this study, we noted that airflow has no immediate effect on relaxation, which was not surprising considering participants were concurrently performing stressful primary tasks. Moreover, due to the study duration, participants did not have time to habituate to the device. When given more time to adjust and familiarize with the device, the impact on relaxation may be altered, and the interactions may shift to be more implicit. To determine these effects, a longer in-the-wild study is necessary where participants can interact with the devices in their daily lives and adapt the use scenarios to their habits, including their work and break schedules. To further understand how breathing with the airflow cues becomes implicit, continuous assessments for attention and workload are necessary, as well as direct comparisons of guided breathing during work and during a break. Additionally, considering qualitative feedback, airflow guides need to be more personalized, such as customizing the intensity of airflow, synchronizing the breathing pattern with each participant, and potentially adjusting the temperature or scent of airflow.

## 7 CONCLUSION

We presented BreathePulse, an airflow-based device mimicking natural breathing patterns to provide implicit guided breathing during information work. We conducted the first study focusing on airflow as a medium for guided breathing, evaluating its feasibility and immediate effects on breathing, stress, anxiety, and affect, and associations with attention and workload during concurrent cognitive tasks. Our findings indicate that pulsing airflow effectively reduced respiratory rate across all tasks, but the reduction was maintained longest (above 40%) during easy tasks. Although the airflow guide had no significant impact on stress levels physiologically or psychologically, it promoted mindfulness. The airflow guide needed minimal attention to be effective, but increased perceived workload. Our combined quantitative and qualitative analyses on workload suggest that cue saliency and attention were key factors affecting the workload of breathing guides. Lastly, we presented guidelines for how to consider workload and attention for different use scenarios. Our work broadens the applications of guided breathing in the workplace by demonstrating airflow as an effective, low-cost, and flexible modality.

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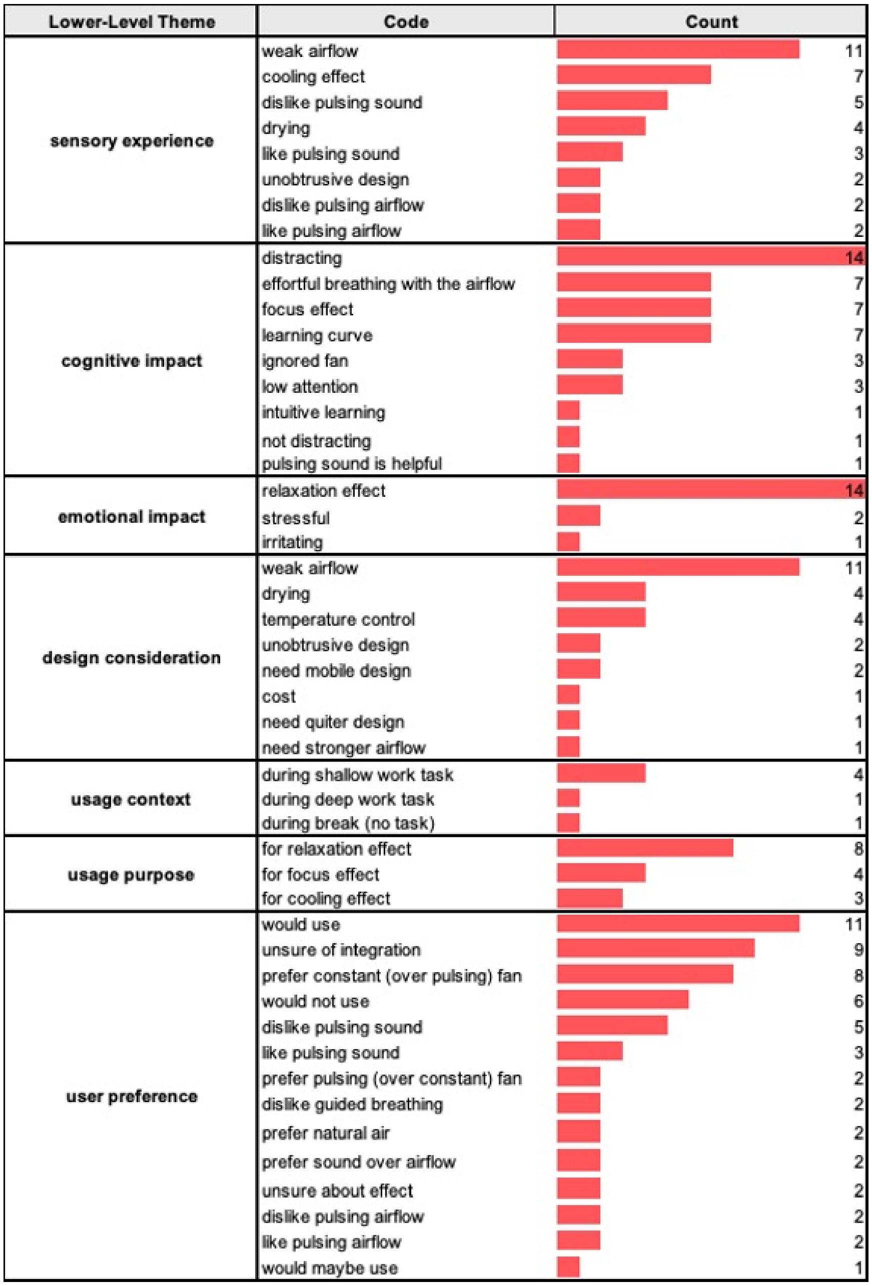
# A CODEBOOK GENERATED FROM OPEN-ENDED QUESTIONS ABOUT PARTICIPANTS' EXPERIENCE AND PERCEPTION OF THE AIRFLOW BREATHING DEVICE



| Lower-Level Theme | Code | Count |
|---|---|---|
| **sensory experience** | weak airflow | 11 |
| | cooling effect | 7 |
| | dislike pulsing sound | 5 |
| | drying | 4 |
| | like pulsing sound | 3 |
| | unobtrusive design | 2 |
| | dislike pulsing airflow | 2 |
| | like pulsing airflow | 2 |
| **cognitive impact** | distracting | 14 |
| | effortful breathing with the airflow | 7 |
| | focus effect | 7 |
| | learning curve | 7 |
| | ignored fan | 3 |
| | low attention | 3 |
| | intuitive learning | 1 |
| | not distracting | 1 |
| | pulsing sound is helpful | 1 |
| **emotional impact** | relaxation effect | 14 |
| | stressful | 2 |
| | irritating | 1 |
| **design consideration** | weak airflow | 11 |
| | drying | 4 |
| | temperature control | 4 |
| | unobtrusive design | 2 |
| | need mobile design | 2 |
| | cost | 1 |
| | need quiter design | 1 |
| | need stronger airflow | 1 |
| **usage context** | during shallow work task | 4 |
| | during deep work task | 1 |
| | during break (no task) | 1 |
| **usage purpose** | for relaxation effect | 8 |
| | for focus effect | 4 |
| | for cooling effect | 3 |
| **user preference** | would use | 11 |
| | unsure of integration | 9 |
| | prefer constant (over pulsing) fan | 8 |
| | would not use | 6 |
| | dislike pulsing sound | 5 |
| | like pulsing sound | 3 |
| | prefer pulsing (over constant) fan | 2 |
| | dislike guided breathing | 2 |
| | prefer natural air | 2 |
| | prefer sound over airflow | 2 |
| | unsure about effect | 2 |
| | dislike pulsing airflow | 2 |
| | like pulsing airflow | 2 |
| | would maybe use | 1 |

Fig. 15. Codebook for qualitative analysis.

## B RESULTS WITH DETAILED STATISTICAL REPORTING

We report how we constructed LMEs and selected the best-performing LMEs as well as the global main effects and interactions for STAI, PANAS, HRV, and NASA-TLX to support the validity of our statistical tests. These results were not included in the paper body to be mindful about the length of the paper.

### B.1 STAI, PANAS, and HRV

We evaluated the effect of experimental conditions on relaxation as measured in state anxiety, negative affect, positive affect, and HRV (reported in RMSSD). Self-reported metrics were collected after each block but not after each task difficulty (Figure 4). Thus, we only examined the effect of experimental conditions on *state anxiety, negative affect, and positive affect* ratings. We also explored the effect of time, as represented by the experimental blocks, as we anticipated that time alone might influence participants ratings on these measures. Our analysis revealed no significant main effects of airflow condition on state anxiety (constant $p = 0.237$; pulsing $p = 0.980$), positive affect (constant $p = 0.381$, pulsing $p = 0.892$), and negative affect (constant $p = 0.424$, pulsing $p = 0.904$, ). While adding the main effect of block to the models significantly improved the model's fit for both the state anxiety ($\chi^2(2) = 10.28, p = 0.006$) and negative affect ($\chi^2(2) = 26.05, p < 0.001$) models, it did not for positive affect model ($\chi^2(2) = 0.12, p = 0.744$). The main effects of block were significant in both anxiety (block 2 $\beta = -1.52, 95\%CI = [-2.78, -0.26], p = 0.019$; block 3 $\beta = -1.95, 95\%CI = [-3.21, -0.68], p = 0.003$ ) and negative affect ($\beta = -2.01, 95\%CI = [-2.76, -1.25], p < 0.001$) models, but not in the positive affect model (block 2$p = 0.600$, block 3 $p = 0.493$). Finally, adding the condition × block interaction term to the anxiety, negative affect, and positive affect models did not improve fit, and this interaction was not significant in all models ($ps > 0.05$). Taken together, these results indicated that participants' anxiety, negative affect, and positive affect ratings did not significantly differ based on the airflow condition but were significantly different between the experimental blocks in the study (Figure 13). Our post-hoc pairwise comparisons using Bonferroni correction across the experimental conditions revealed that the main effect of block on state anxiety and negative affect were due to significantly higher ratings of anxiety in block 1 relative to block 3 ($\Delta M = 1.95, t = 3.08, p < 0.012$), and significantly higher ratings of negative affect in block 1 relative to block 2 ($\Delta M = 3.08, t = 4.20, p < 0.001$) and block 3 ($\Delta M = 4.01, t = 5.39, p < 0.0001$; Figure 13)

We also examined the effect of experimental conditions and task difficulty on HRV. The main effect of experimental conditions on RMSSD was driven by constant airflow, which had a significant effect compared to no airflow ($p = 0.027$). Adding the effect of task difficulty marginally insignificantly improved the model fit ($\chi^2 = 3.79, p = 0.052$). Since we designed the study to probe for the effect of task difficulty, we accepted the model adding task difficulty. There was no interaction between task difficulty and conditions. Adding the effect of the block did not improve the model fit (p = 0.22). The best-fitting model showed that the constant airflow significantly decreased RMSSD ($\beta = -5.66, CI = [-10.68, -0.65], p = 0.027$), but the pulsing airflow did not ($p = 0.186$). The hard task also marginally insignificantly decreased the RMSSD ($p = 0.055$). Post-hoc pairwise comparisons showed no significant differences in RMSSD between no airflow and constant airflow ($p = 0.082$), no airflow and pulsing airflow ($p = 0.560$), or constant airflow and pulsing airflow ($p > 0.999$). Together, these results revealed that neither having the pulsing airflow nor the task difficulty significantly changed the parasympathetic activity of the participants.

### B.2 NASA TLX

We examined workload associated with breathing with and without the airflow guide when participants were engaged in different levels of cognitive task (easy and hard). Specifically, we assessed the experimental conditions × task difficulty interaction effect on perceived mental demand, physical demand, effort, frustration, and reduced performance as well as total workload. We also explored the effect of time (i.e., experimental blocks) and its interaction effect with experimental conditions and task difficulty on these measures.

*B.2.1 Mental Demand.* We found significant main effects of condition (constant airflow: $\beta = 0.24, 95\%CI = [-1.20, 1.69], p = 0.738$; pulsing airflow:$\beta = 1.55, 95\%CI = [0.10, 3.00], p = 0.036$), task difficulty ($\beta = 5.26, 95\%CI = [4.08, 6.44], p < 0.001$), and block (block 2: $\beta = -2.20, 95\%CI = [-3.64, -0.75], p = 0.003$; block 3: $\beta = -3.03, 95\%CI = [-4.48, -1.58], p < 0.001$). The addition of block main effect significantly improved fit ($\chi^2(2) = 17.72, p < 0.001$) while the addition of experimental condition × task difficulty did not ($\chi^2(4) = 0.952, p = 0.917$). Additionally, there were no significant condition × task difficulty or condition × block or task difficulty × block interaction effects ( $ps > 0.05$). These results indicated that mental demand increases with increasing task difficulty across experimental conditions and blocks and in pulsing airflow condition regardless task difficulty and block. In contrast, this perceived mental demand decreases with increasing block (i.e., time), regardless of experimental conditions and task difficulty.

Post-hoc pairwise comparison using Bonferroni correction showed that the main effect of block was driven by the fact that perceived mental demand was significantly higher in block 1 relative to block 2 ($\Delta M = 2.20, t = 3.01, p < 0.010$) and block 3 ($\Delta M = 4.01, t = 5.39, p < 0.0001$; Figure 12 (A)) across all task levels and conditions. Our post-hoc pairwise comparison also revealed no significant difference between the no airflow and the pulsing airflow conditions ($p = 0.120$), the no airflow and the constant airflow conditions ($p > 0.999$), and the constant airflow and the pulsing airflow conditions ($p = 0.230$), suggesting that mental demand reported for each condition in all blocks and task levels did not significantly differ from each other.

*B.2.2 Effort.* We found significant main effects of condition (constant airflow: $\beta = 0.19, 95\%CI = [-1.21, 1.58], p = 0.792$; pulsing airflow:$\beta = 1.62, 95\%CI = [0.23, 3.01], p = 0.023$), and task difficulty ($\beta = 3.75, 95\%CI = [2.63, 4.89] p < 0.001$). However, adding the interaction effect of experimental condition × task difficulty to the model did not improve fit $\chi^2(2) = 5.54, p = 0.063$). Adding the block main effect significantly improved fit ($\chi^2(2) = 11.17, p = 0.004$) and that the block main effect was significant (block 2: $\beta = -1.43, 95\%CI = [-2.82, -0.05], p = 0.043$; block 3: $\beta = -2.33, 95\%CI = [-3.73, -0.94], p = 0.001$). Additionally, the addition of airflow condition × block $\chi^2(4) = 2.52, p = 0.642$) or task difficulty × block interaction effects $\chi^2(2) = 1.70, p = 0.427$) worsened the model's fit. These findings demonstrated that moving from no airflow to pulsing airflow condition, adjusted for task difficulty and blocks, as well as higher task difficulty level and later experimental blocks were associated with increased perceived effort.

Our further post-hoc pairwise analyses with Bonferroni correction on the differences in perceived effort among the airflow conditions showed no significant difference in effort ratings between the no airflow and the pulsing airflow conditions ($p = 0.069$), the no airflow and the constant airflow conditions ($p > 0.999$), and the constant airflow and the pulsing airflow conditions ($p = 0.130$), which suggests that perceived effort in the three conditions did not significantly differ from each other when adjusted for all blocks and task levels; Figure 12(B). However, our post-hoc analysis on the difference in effort ratings among blocks, regardless of task levels and airflow conditions, indicated that participants reported significantly higher level of effort in block 1 relative to block 3 ($\Delta M = 2.33, t = 3.32, p = 0.004$), but the perceived ratings were not significantly different between block 1 and block 3 ($\Delta M = 1.43, t = 2.05, p = 0.130$) and between block 2 and 3 ($\Delta M = 0.90, t = 1.28, p = 0.611$).

*B.2.3 Frustration.* Our best fitting model indicated a statistically significant main effect of task difficulty ($\beta = 3.00, 95\%CI = [1.84, 4.16] p < 0.001$) but not significant main effect of airflow condition (constant $p = 0.830$; pulsing $p = 0.241$). The addition of airflow condition × task difficulty worsened the model, whereas the addition of block main effect led to a statistically significant improvement in the model's fit $\chi^2(4) = 22.215, p < 0.001$; block 2: $\beta = -2.02, 95\%CI = [-3.45, -0.60], p = 0.006$; block 3: $\beta = -3.48, 95\%CI = [-4.91, -2.05], p < 0.001$). We explored adding the interaction terms for condition × block and task difficulty × block interaction effects, but both did not improve fit ($ps > 0.05$).

Subsequent pairwise comparisons between the blocks with Bonferroni correction showed that participants reported higher levels of frustration in block 1 compared to block 2 ($\Delta M = 2.02, t = 2.81, p < 0.018$) and block 3 ($\Delta M = 3.48, t = 4.82, p < 0.001$), but frustration levels did not differ significantly between block 2 and 3 ($\Delta M = 1.46, t = 2.02, p = 0.139$; Figure 12 (C)). Taken together, these results showed that, while participants' frustration level was influenced by task difficulty and time (block), it was not significantly influenced by the experimental conditions.

*B.2.4 Physical Demand.* In the final model, we found significant main effects of condition (constant airflow: $\beta = 1.15, 95\%CI = [-0.13, 2.43], p = 0.077$; pulsing airflow:$\beta = 2.52, 95\%CI = [1.24, 3.80], p < 0.001$) and task difficulty ($\beta = 1.68, 95\%CI = [0.64, 2.73], p = 0.002$). The addition of experimental block main effect ($\chi^2(2) = 2.07, p = 0.355$) and condition × task difficulty ($\chi^2(2) = 1.27, p = 0.530$) did not improve the model fit. Adding the condition × block or task difficulty × block interaction effects ($ps > 0.05$). These results suggests that increased task difficulty and being in the constant or the pulsing airflow condition relative to the no airflow condition is associated with increased physical demand.

We conducted post-hoc pairwise comparison using Bonferroni correction to explore differences in physical demand ratings between airflow conditions and found that while perceived physical demand was significantly higher in the pulsing relative to the no airflow condition ($\Delta M = -2.52, t = -3.90, p < 0.001$), it was not significantly different between the pulsing and constant airflow ($\Delta M = -1.37, t = -2.12, p = 0.109$) and between the constant and no airflow condition ($\Delta M = -1.15, t = -1.78, p = 0.233$; Figure 12 (D)).

*B.2.5 Reduced Performance.* Our final model revealed statistically significant main effects of airflow conditions (constant $\beta = 1.82, 95\%CI = [0.33, 3.30], p = 0.017$; pulsing $\beta = 3.56, 95\%CI = [2.07, 5.04], p < 0.001$;), task difficulty ($\beta = 4.68, 95\%CI = [3.47, 5.89] p < 0.001$), and block (block 2: $\beta = -2.93, 95\%CI = [-4.41, -1.46], p < 0.001$; block 3: $\beta = -3.38, 95\%CI = [-5.31, -2.35], p < 0.001$). Adding the interaction effect of airflow condition × task difficulty did not improve fit $\chi^2(2) = 0.76, p = 0.684$, whereas the addition of block main effect led to a statistically significant improvement in the model's fit ($\chi^2(2) = 26.615, p < 0.001$). We explored adding the interaction terms for condition × block and task difficulty × block interaction effects, but both did not improve fit ($ps > 0.05$).

Our post-hoc analyses on differences among the three conditions showed that participants perceived higher reduction in performance in pulsing airflow condition relative to the no airflow condition ($\Delta M = -3.56, t = -4.74, p < 0.001$) ) but not in the constant airflow condition compared to the no airflow condition ($\Delta M = -1.82, t = -2.42, p < 0.051$); Figure 12 (E)).

Additionally, our post-hoc pairwise comparisons among the three blocks, adjusted for airflow conditions and task levels, demonstrated that participants reported higher perceived reduction in performance in block 1 compared to when they were in block 2 ($\Delta M = 2.94, t = 3.93, p < 0.001$) and block 3 ($\Delta M = 3.83, t = 5.11, p < 0.001$). These findings suggest that participants perceived worse performance when they were in pulsing and constant airflow conditions compared to no airflow condition, and when doing harder cognitive tasks and later in the study experiment (i.e., temporal effect).

*B.2.6 Total Workload.* Our final model revealed statistically significant main effects of airflow conditions (constant $\beta = 3.06, 95\%CI = [-2.66, 8.78], p = 0.292$; pulsing $\beta = 10.36, 95\%CI = [4.64, 16.08], p < 0.001$), task difficulty ($\beta = 20.71, 95\%CI = [16.05, 25.37] p < 0.001$), and block (block 2: $\beta = -11.67, 95\%CI = [-17.38, -5.97], p < 0.001$; block 3: $\beta = -16.66, 95\%CI = [-22.38, -10.93], p < 0.001$). Adding the interaction effect of airflow condition × task difficulty did not improve fit $\chi^2(2) = 0.437, p = 0.804$, whereas the addition of block main effect led to a statistically significant improvement in the model's fit ($\chi^2(2) = 31.779, p < 0.001$). We explored adding the interaction terms for condition × block and task difficulty × block interaction effects, but both did not improve fit ($ps > 0.05$).

Our post-hoc analyses on differences among the three conditions showed that participants perceived higher reduction in performance in pulsing airflow condition relative to the no airflow condition ($\Delta M = -10.36, t = -3.58, p = 0.002$) ) and in the pulsing airflow condition compared to the constant airflow condition ($\Delta M = -7.30, t = -2.53, p < 0.038$) ), but not in the constant relative to the no airflow condition ($p = 0.877$; Figure 12(F)).

Additionally, our post-hoc pairwise comparisons among the three blocks, adjusted for airflow conditions and task levels, demonstrated that participants reported higher perceived reduction in performance in block 1 compared to when they were in block 2 ($\Delta M = 2.94, t = 3.93, p < 0.001$) and block 3 ($\Delta M = 3.83, t = 5.11, p < 0.001$). These findings suggest that participants perceived worse performance when they were in pulsing airflow conditions compared to the constant airflow and no airflow condition, and when doing harder cognitive tasks and later in the study experiment (i.e., temporal effect).