A Mobile Health Application and System Architecture for Respiratory Disease Management: Design Principles, Tool Development and Pilot Usability Test

Andrew Chao, Lisa Martignetti, René Groh, Andreas M. Kist, Nicole Y. K. Li-Jessen

Submitted to: JMIR Formative Research
on: March 07, 2025

Table of Contents

A Mobile Health Application and System Architecture for Respiratory Disease Management: Design Principles, Tool Development and Pilot Usability Test

Andrew Chao[1]; Lisa Martignetti[1]; René Groh[2]; Andreas M. Kist[2]; Nicole Y. K. Li-Jessen[3]

[1] McGill University Montreal, Quebec CA
[2] Friedrich-Alexander-Universität Erlangen-Nürnberg Erlangen DE
[3] McGill University Montreal CA

Corresponding Author:
Nicole Y. K. Li-Jessen

McGill University
2001 McGill College , 8th floor
Montreal
CA

Abstract

Background: Mobile health (mHealth) apps are essential software interfaces that enable users to access and manage wearable health technology through smartphones and tablets. However, many respiratory disease mHealth apps lack transparent development documentation, compromising user confidence in their quality, functionality, and usability.

Objective: This study aimed to develop and evaluate AIrway, a companion mHealth app designed to interface with an in-house wearable device for monitoring airway symptoms following established mHealth development and reporting standards.

Methods: The development cycle of AIrway comprised three study phases. In Phase 1, a comprehensive needs assessment was conducted to identify the required features of a mHealth app targeted at asthma and COPD monitoring. In Phase 2, AIrway, a native Android app, was developed following academic and industrial standards (Android Material design, Morville's design principles) and privacy regulations (Personal Information Protection and Electronic Documents Act). Core functionalities included location-based environmental monitoring, a clinical diary with action plans, Bluetooth connectivity, and real-time data storage. In Phase 3, the usability of AIrway was evaluated by software app developers using standardized assessment tools, namely, the uMARS survey and IQVIA questionnaire.

Results: AIrway successfully fulfilled seven of eight development criteria on usability, privacy, security, appropriateness, transparency, safety, and technical support, with only the technology aspects requiring refinement. Accessibility assessments confirmed that AIrway's content and interface were comprehensible to the general population (Grade 9-10 reading level). Technical testing demonstrated reliable Bluetooth data transmission for up to 10 minutes without interruption. User evaluation scores for uMARS (3.6/5.0) and IQVIA (8/11) were comparable to those of similar mHealth applications on the market.

Conclusions: By adhering to established mHealth application design principles, AIrway achieved the necessary accessibility standards and wireless communication capabilities for wearable device integration. Future development will focus on expanding cross-platform compatibility and conducting usability evaluation with actual patient populations to validate AIrway's clinical effectiveness and support ongoing improvements.

(JMIR Preprints 07/03/2025:73584)
DOI: https://doi.org/10.2196/preprints.73584

Preprint Settings

1) Would you like to publish your submitted manuscript as preprint?

✔ **Please make my preprint PDF available to anyone at any time (recommended).**
Please make my preprint PDF available only to logged-in users; I understand that my title and abstract will remain visible to all users.
Only make the preprint title and abstract visible.

No, I do not wish to publish my submitted manuscript as a preprint.

2) If accepted for publication in a JMIR journal, would you like the PDF to be visible to the public?

✓ **Yes, please make my accepted manuscript PDF available to anyone at any time (Recommended).**

Yes, but please make my accepted manuscript PDF available only to logged-in users; I understand that the title and abstract will remain v

Yes, but only make the title and abstract visible (see Important note, above). I understand that if I later pay to participate in <a href="http

No. Please do not make my accepted manuscript PDF available to anyone.

Original Manuscript

A Mobile Health Application and System Architecture for Respiratory Disease Management: Design Principles, Tool Development and Pilot Usability Test

Andrew Chao, MSc[1,2], Lisa Martignetti, MSc[1], René Groh, MSc[3], Andreas M. Kist, PhD[3], Nicole Li-Jessen, PhD[1,2,4,5,6]

[1] School of Communication Sciences and Disorders, Faculty of Medicine and Health Sciences, McGill University, Quebec, Canada

[2] Department of Biomedical Engineering, McGill University, Montreal, Quebec, Canada

[3] Department Artificial Intelligence in Biomedical Engineering, Friedrich-Alexander-Universität Erlangen-Nürnberg, Erlangen, Germany

[4] The Centre for Research on Brain, Language and Music, McGill University, Montreal, Quebec, Canada

[5] Department of Otolaryngology - Head and Neck Surgery, McGill University, Montreal, Quebec, Canada

[6] Translational Research in Respiratory Diseases Program, Research Institute of McGill University Health Center, Montreal, Quebec, Canada

Andrew Chao
usan.chao@mail.mcgill.ca

Lisa Martignetti
lisa.martignetti@mail.mcgill.ca

René Groh
rene.groh@fau.de

Andreas M. Kist
andreas.kist@fau.de

Correspondence to: Nicole Li-Jessen; nicole.li@mcgill.ca; 2001 McGill College Ave, 8th Floor, Montreal, Quebec, H3A 1G1, Canada

Abstract

Background: Mobile health (mHealth) apps are essential software interfaces that enable users to access and manage wearable health technology through smartphones and tablets. However, many respiratory disease mHealth apps lack transparent development documentation, compromising user confidence in their quality, functionality, and usability.

Objectives: This study aimed to develop and evaluate *AIrway*, a companion mHealth app designed to interface with an in-house wearable device for monitoring airway symptoms following established mHealth development and reporting standards.

Methods: The development cycle of *AIrway* comprised three study phases. In Phase 1, a comprehensive needs assessment was conducted to identify the required features of a mHealth app targeted at asthma and COPD monitoring. In Phase 2, *AIrway*, a native Android app, was developed following academic and industrial standards (Android Material design, Morville's design principles) and privacy regulations (Personal Information Protection and Electronic Documents Act). Core functionalities included location-based environmental monitoring, a clinical diary with action plans, Bluetooth connectivity, and real-time data storage. In Phase 3, the usability of *AIrway* was evaluated by software app developers using standardized assessment tools, namely, the uMARS survey and IQVIA questionnaire.

Results: *AIrway* successfully fulfilled seven of eight development criteria on usability, privacy, security, appropriateness, transparency, safety, and technical support, with only the technology aspects requiring refinement. Accessibility assessments confirmed that *AIrway*'s content and interface were comprehensible to the general population (Grade 9-10 reading level). Technical testing demonstrated reliable Bluetooth data transmission for up to 10 minutes without interruption. User evaluation scores for uMARS (3.6/5.0) and IQVIA (8/11) were comparable to those of similar mHealth applications on the market.

Conclusion: By adhering to established mHealth application design principles, *AIrway* achieved the necessary accessibility standards and wireless communication capabilities for wearable device integration. Future development will focus on expanding cross-platform compatibility and conducting usability evaluation with actual patient populations to validate *AIrway*'s clinical effectiveness and support ongoing improvements.

Keywords: Asthma, COPD, Development guidelines and standards, Mobile health apps, Usability assessment, Wearable devices

List of Acronyms and Abbreviations

COPD	Chronic Obstructive Pulmonary Disease
App	Application – the term mobile app refers to mobile software application
mHealth	Mobile Health
UI	User Interface
UX	User Experience
NSA	Neck Surface Accelerometer
AQHI	Air Quality Health Index
BLE	Bluetooth Low Energy
uMARS	The User Version of the Mobile Application Rating Scale – a usability questionnaire that consists of 23 questions in four dimensions: engagement, functionality, aesthetics, and information quality
IQVIA	IQVIA is previously known as Intercontinental Medical Statistics (IMS) score– a usability survey that consists of 11 items related to self-management app functions
GINA	Global Initiative for Asthma – an international medical organization established by the World Health Organization and the US National Heart Lung and Blood Institute to provide guidelines on asthma
GOLD	Global Initiative for Chronic Obstructive Lung Disease – an international medical organization established by the World Health Organization and the US National Heart Lung and Blood Institute to provide guidelines on COPD

Introduction

The rapid evolution of wearable health technology has transformed the remote monitoring of patients with chronic respiratory diseases, such as asthma and chronic obstructive pulmonary disease (COPD). These conditions are often marked by sudden symptom exacerbations – triggered by factors like smoke exposure – that can escalate into life-threatening emergencies requiring immediate medical attention. Wearable technology offers a promising solution by enabling early detection of these flare-ups, empowering patients to proactively manage their airway conditions and enhance their quality of life [1]. Research to date has shown that wearable health tools can increase medication adherence by 50% through reminders and improve patients' disease-related knowledge by 52%, significantly enhancing disease management [2].

Monitoring airway-related symptoms poses distinct challenges that require tailored wearable sensing technologies in respiratory care. Advanced surface body sensors need to accurately capture critical physiological data, including heart rate, skin temperature, and breathing patterns. Acoustic microphones, while effective for data capture, present significant privacy concerns for continuous monitoring as they inevitably record identifiable speech [3-5]. In contrast, neck surface accelerometers (NSAs) provide a privacy-preserving solution by capturing purely mechano-acoustic signals without speech content, making them well-suited for long-term monitoring of chronic respiratory conditions such as asthma and COPD [6-10]. Recent studies highlight the effectiveness of NSAs in detecting voice physiology, swallowing events and COPD severity indicators. By applying advanced machine learning techniques, such as ensemble deep learning and convolutional neural networks, NSA-based systems have been shown to achieve prediction accuracies ranging from 93% to 96% for various respiratory parameters [11-13].

Successful implementation of wearable health technologies depends on a well-defined data pathway and an effective mobile interface. Raw sensor data captured by wearable devices are first stored in onboard flash memory before being transmitted via Bluetooth Low Energy (BLE) to mobile devices, such as smartphones and tablets. These data then undergo further processing and analysis on computers or cloud-based servers for comprehensive evaluation. Dedicated mobile health (mHealth) apps, installed on mobile devices, are required to process and visualize the wearable data, delivering real-time health insights to users [14-16]. Beyond data presentation, many mHealth apps [17-19] incorporate interactive features, such as self-assessment questionnaires and chatbots, to promote healthier behaviors.

Standardized Android platforms are commonly used for mHealth app development to facilitate data acquisition, visualization, and device control. However, many published reports [20, 21] lack adequate documentation of their mHealth app development processes, presenting a significant barrier to the clinical adoption of wearable technologies. Given that mHealth apps serve as the primary interface between users and wearable devices, a transparent development process is essential for establishing user confidence. Without proper documentation of quality assurance, functionality, and usability testing, wearable health technologies remain limited in their ability to support remote healthcare delivery and patient self-management for respiratory conditions.

In this study, we developed an mHealth app, *AIrway*, designed to integrate with our custom NSA wearable device for detecting and monitoring airway symptoms in patients with asthma or COPD. The development process adhered to rigorous academic and industry standards, with comprehensive documentation and reporting. A pilot study was conducted with app developers to evaluate *AIrway*'s usability and functionality. This paper is structured as follows. The Methods section outlines the three study phases of *AIrway*'s development: needs assessment (Phase 1), frontend and backend development (Phase 2), and a pilot usability test (Phase 3). The Results section presents findings from analyses of content readability and accessibility, BLE connectivity tests with the wearable device, and usability evaluations from the pilot study. The Discussion section compares *AIrway* with existing digital health solutions, discusses its limitations, and outlines future research directions.

Methods

Phase 1: Needs Assessment for *AIrway*

Feature Requirements

To establish the feature requirements for the *AIrway* app targeting chronic airway diseases like asthma and COPD, a multidisciplinary team including clinicians, researchers, and app developers conducted a comprehensive needs assessment of the mHealth app market to identify common functionalities and critical gaps. We identified three types of mHealth solutions for airway disease monitoring (**Table 1**). The first type involves a commercial smartwatch device and a corresponding app, such as the Apple Watch [22] and Fitbit [23]. These smartwatches are equipped with a range of biosensors, such as accelerometers and temperature sensors, to capture an individual's physiological data. The apps display the relevant results. The devices are purchased separately, while the apps are generally available for free download. The second type utilizes customized wearable devices, such as Afflo [24] and AcuPebble [25], paired with dedicated apps. These devices incorporate modules like microphones to collect audio samples, which are analyzed on the device using machine learning algorithms to predict respiratory health outcomes. The results are then displayed in the apps. Typically, the customized device and the app are fabricated by contract manufacturers and software companies. The third type involves standalone apps, such as Breathe [26], Sonde Health [27], and CoughPro [28], that do not require external sensors. Instead, they use integrated features such as chatbots, or clinical questionnaires combined with machine learning algorithms to predict respiratory outcomes based on user inputs. Many of these apps are open-source and available for free download from app stores.

Table 1. Commercial wearable devices and apps for respiratory health.

Product	Type	Hardware	Data Acquisition	Data Visualization
Apple Watch [22]	Smartwatch paired with an Android or iOS app	Blood oxygen sensor, heart rate sensor, accelerometer, gyroscope	Physiological signals based on sensors via Bluetooth	Fitness tracking, step count, blood oxygen level, sleep patterns
Fitbit [23]	Smartwatch paired with an Android or iOS app	Accelerometer, heart rate sensor, barometer, temperature sensor, gyroscope	Physiological signals based on sensors via Bluetooth	Fitness tracking, skin temperature, stress management, sleep pattern
Afflo [24]	A customized wearable device attached to the chest and an iOS app	Embedded microphone module on the wearable device	Wheeze, cough, inhaler audio samples from the device via Bluetooth. Use APIs to retrieve air pollution	Use AI to predict asthma outcomes Current air pollution, and medication results
AcuPebble [25]	A customized wearable device	Embedded acoustic sensor on	Using an acoustic sensor to capture	Identify breathing segments and

	to the base of the neck paired with an app on iOS and Android	the wearable device	physiological sounds from respiratory and cardiac functions	extract cardiac information for diagnosing sleep apnea
Breathe [26]	A standalone iOS app	No external hardware is required	Use of a chatbot to gather user clinical information	Provide customized advice based on asthma and COPD action plans and send reminders
Sonde Health [27]	A standalone iOS and Android app	Use smartphone's microphone to collect voice sample	User questionnaire, voice sample (e.g., say "ahhh" for 6 seconds	Respiratory score (0 - 100)
CoughPro by Hyfe AI [28]	A standalone iOS and Android App	Use smartphone's microphone to collect cough samples	Cough sample from the users	Use AI to predict cough and provide a summary of user's cough
AIrway (Chao et al. of this study)	An Android app paired with a customized wearable device	A Privacy-preserving wearable device with embedded Bluetooth and AI capabilities	User questionnaire, OpenWeatherMap API to retrieve environmental conditions, real-time monitoring of airway symptoms	Provide a personalized account, and customized advice based on asthma and COPD action plans

Existing mHealth solutions typically prioritize the collection and visualization of general physiological data over the development of comprehensive management systems. For instance, devices such as the Apple Watch and Fitbit provide metrics like oxygen levels and heart rates but lack disease-specific insights and personalized interventions essential for managing conditions such as asthma and COPD. Similarly, wearables like Afflo and AcuPebble capture respiratory signals (e.g., wheezing and coughing) but fail to translate these data into actionable self-management strategies. Additionally, standalone applications relying on acoustic microphone samples or chatbots to deliver clinical recommendations not only raise significant privacy concerns but also lack continuous, real-time sensor data to monitor changes in vital signs indicative of a user's health status.

Unlike existing solutions, *AIrway* uniquely integrates with our NSA wearable device, enabling continuous mechano-acoustic data transmission to the mobile device through BLE technology. This integration supports efficient data storage, management, and visualization while maintaining patient privacy through secure cloud services. The app’s intuitive user interfaces, featuring clear navigation and graphical displays, simplify data management and visualization. In sum, *AIrway* was designed to harness multiple data streams – including NSA wearable-derived symptom classifications, patient-reported outcomes, and environmental metrics – to enhance patient self-management and enable prompt interventions, setting it apart as a proactive health management tool. By combining wearable data with patient-reported outcomes and environmental factors, *AIrway* is expected to provide personalized exacerbation risk predictions and targeted recommendations, distinguishing it from conventional mHealth solutions and offering patients a comprehensive tool for proactive respiratory health management.

mHealth App Guidelines and Requirements

Adhering to established guidelines and standards is crucial for developing safe, user-friendly, and regulatory-compliant mHealth apps. For instance, Apple’s Human Interface Guidelines [29] and Android’s Material Design Guidelines [30] provide direction on the app’s aesthetics, including positioning user interface components, setting minimum text sizes, and optimizing color contrast ratios. Similarly, the European Commission’s Green Paper on Mobile Health [31] and the Mobile Medical Applications: Guidance for Food and Drug (U.S.) [32] provide recommendations for privacy and security, covering access control, data transfer, and encryption, particularly for apps that require user authentication and wireless data transmission.

The Xcertia Guidelines, developed by members of the American Medical Association (AMA) and the American Heart Association (AHA), present actionable practices to improve apps’ privacy, security, usability, operability, and content [33]. Developers handling protected health information (PHI) must comply with the Health Insurance Portability and Accountability Act (HIPAA) in the United States or equivalent regulations in their regions [34]. Additionally, personal data (e.g., usernames and passwords) should be encrypted using industry-accepted methods (e.g., FIPS 140-2, ISO/IEC). Explicit user consent is required before data collection.

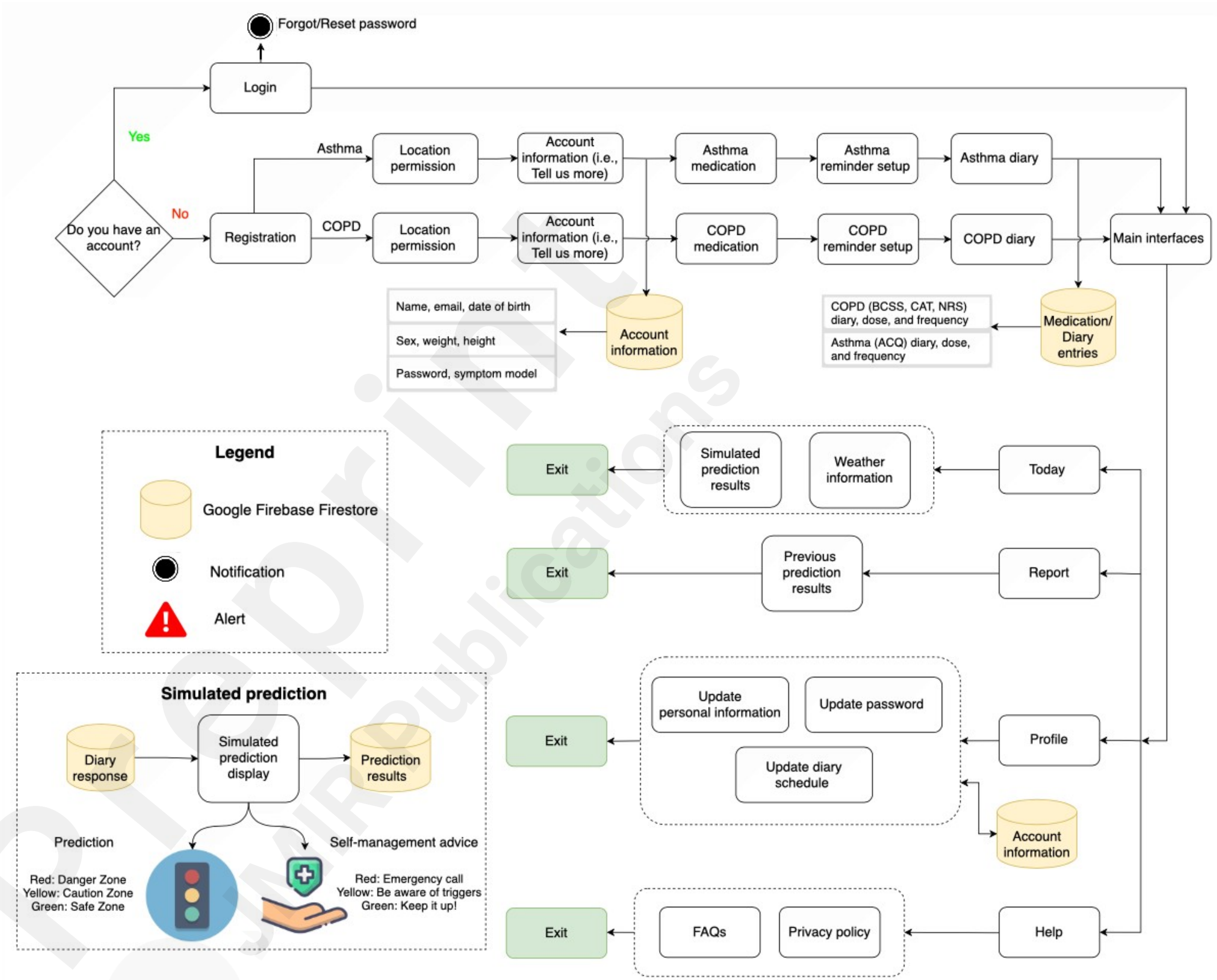
Furthermore, a seminal paper "*Standards for Mobile Health–Related Apps: Systematic Review and Development of a Guide*" [35] presents a comprehensive framework that integrates published studies, guidelines, and standards for health app development with feedback from developers, patients, and healthcare professionals. This framework proposes eight criteria: usability, privacy, security, appropriateness and suitability, transparency and content, safety, technical support and updates, and technology. In this study, such framework would be employed to validate if *AIrway* met the best practice of mHealth app development.

Phase 2a: Frontend Development

App Interface Implementation and Workflow

The *AIrway* UI was set up using XML (version 1.0) [36] in Android Studio (Chipmunk 2021.2.1 version) [37], a Google native Android development integrated development platform (IDE). The IDE allowed developers to build Android applications on Windows, Mac, and Linux operating systems. The app supported respiratory disease management with two types of interfaces. Task-based interfaces allowed users to create a personalized account and log in, manage location permissions, input medication details, log symptoms via a clinical diary, and set diary reminders. Meanwhile, visualization interfaces displayed local weather, action plans, health data summaries, and provided account and app privacy information (**Figure 1**).

Figure 1. *AIrway* design flowchart.



Design Principles

Morville's design principles [38] were followed to guide the UX and UI design of *AIrway* (**Table 2**). In brief, Morville's principles include seven aspects of user experience for mobile apps and websites: usefulness, value, findability, credibility, accessibility, desirability, and usability. These principles have been widely adopted in mHealth apps such as an emotional and physical health support app for the elderly [39] and a post-traumatic stress monitoring app [40].

For *AIrway*, the end users are individuals with asthma or COPD, who are often elderly. To apply Morville's principles for the app, the UX and UI were built with simplified user interfaces, large texts, easy-to-use navigation buttons, and motivational functions, such as reminders to keep users engaged and encouraged for continued usage [41].

Table 2. Adaptation of Morville's design principles for *AIrway* [38].

Design Principle	Question and answer
Usefulness	Q1: Does the app have practical value for the target users? • The app allowed the target users (i.e., patients with asthma and/or COPD) to create a personalized account, monitor their conditions, and predict airway conditions through a clinical diary. It also provided reminders and alerts for diary completion. The app stored the data in a cloud service.
Value	Q2: Does the app advance the mission of the organization behind it? • The *AIrway* app was developed by the Voice and Upper Airway Research Lab at McGill University, Canada, in collaboration with researchers at the University of Erlangen-Nürnberg, Germany. We are improving personalized medicine in voice and upper airway dysfunctions with advanced technology. For this project, we hope to support asthma and COPD management and provide recommended actions to the user.
Findability	Q3: Can users locate what they are looking for? • The app was developed using large fonts, buttons and a navigation menu to assist the user to switch between interfaces. The app also incorporated some frequently asked questions to support the user.
Credibility	Q4: Is the app trustworthy? • The app components were developed based on other mHealth

	apps, such as Fitbit [23], Afflo [24], and Breathe [26]. The clinical diary and prediction results were developed based on clinical guidelines and literature (such as GINA and GOLD). Data is safely stored in Google Cloud Services, which are eligible for HIPAA compliance.
Accessibility	Q5: Are there barriers that may prevent the target users from using the app? • The app was developed based on the Web Content Accessibility Guidelines (WCAG) [42] and readability metrics. For instance, our app used user-friendly colors for the app background and easily understandable written materials for the app content.
Desirability	Q6: Do the target users want to use the app? What are the responses? • A usability study was conducted with app developers. The study protocol was outlined, and the responses were summarized in the Result section.

Optimal Element Layout and Text Font Size

The Android operating system was chosen for deploying *AIrway* across different devices, such as LG, Google Pixel, and Samsung. As these devices can vary significantly in their screen size, the app content display can be altered, and information may become misaligned.

To address this development issue, the app's UI was built using the constraint layout [43] following the Android Material Design Guidelines [30]. Constraint layout allows UI elements (e.g., buttons and texts) to be positioned relative to each other. For instance, the elements can always be specified relative to the top, center, or bottom of the screen using constraint layout in the XML (version 1.0) file [43]. That way, the app's UI components were flexible enough to be adjusted and fit different screen sizes. Besides, Android Guidelines [30] recommend a minimum text size of 20sp (scalable pixels) for titles, 16sp for subtitles, and 14sp for buttons and body to improve readability. These recommendations were adhered to in the development of the app.

Optimal Colour Contrast for App Interfaces

Colour contrast is critical for user accessibility and usability. According to Web Content Accessibility Guidelines (WCAG) [42], texts and images should have a minimum contrast ratio of 7:1 (i.e., AAA compliance). In some cases, a higher contrast ratio may not necessarily be the most suitable choice. The colour contrast of the app's UI components, including the background and button colours, was fine-tuned using an open-source colour contrast checker [44] to ensure the color pairs meet WCAG standards (**Table 3**). The AAA compliance is meant to enhance visibility for users with low vision or reduced contrast sensitivity who do not use assistive technology [45].

Table 3. Color contrast check for the app components.

App text colour	**App background colour**	**Contrast ratio**
#000000 (black)	#ACC8E5 (light blue)	12.15: 1
Button text colour	**Button background colour**	**Contrast ratio**
#FFFFFF (white)	#023753 (dark blue)	12.55: 1
Drop-down menu text colour	**Drop-down menu background colour**	**Contrast ratio**
#000000 (black)	#FFFFFF (white)	21: 1
User input text colour	**User input background colour**	**Contrast ratio**
#000000 (black)	#FFFFFF (white)	21: 1

User Login and Registration

Upon using the app, users first interacted with the Login interface. They could either log in with their credentials or create an account on the Register interface by entering their name, email, password, and selecting a condition to monitor. The email input field included validation checks for proper formatting, and passwords were masked for security. Based on their selection, users were directed to either asthma or COPD-specific interfaces. If users forgot their password, they could request a reset link via a valid email and then log in with the new password (**Appendix I**).

Location Permission

After registration, the app requested access to the device's location to retrieve local weather data. This location permission was declared in the *AndroidManifest.xml* file, with *ACCESS*¿ enabling access to the approximate location without storing it [46]. The app requested the permission at runtime, offering three options: "*While using the app,*" "*Only this time,*" or "*Deny*" (**Appendix I**).

User Account Information

Users provided personal information including their biological sex, date of birth, weight, and height. Biological sex was a drop-down menu with three options: "*Male,*" "*Female,*" and "*Prefer not to say*." A *DatePicker* [47] component allowed users to easily scroll through dates for their date of birth. Input fields for weight and height accepted only numbers, with selectable units: "*kg*" or "*lbs*" for weight and "*m*" or "*ft*" for height (**Appendix I**).

Medication Profile

The medication profile design was based on the guidelines from the Canadian Lung Association [48], the Ontario Lung Association [49] and the Breathe app [26]. Depending on the condition, users filled out either the asthma or COPD profile including the medication name, amount, and frequency. To handle over 10 options without cluttering the UI, a drop-down menu was implemented. This design allowed users to easily select a suitable option with a single click, after which the menu collapsed to display only the selected option, providing a clean UI to users (**Appendix I**).

Clinical Diary

Clinical diaries support patient self-management and remote monitoring. In the case of asthma and COPD, effective self-management and improved healthcare outcomes rely on clinically validated diaries that are user-friendly, relevant to the patient's symptoms and medications, and capable of identifying the predictors of exacerbations [50, 51]. The app was designed to prompt users to fill out the clinical diary (asthma or COPD) daily either after the initial registration or at the scheduled time.

For asthma, the app used the Asthma Control Questionnaire (ACQ) [52], a clinically validated tool recommended by the Global Initiative for Asthma (GINA) [53] comprising five items for assessing asthma symptoms and one item for rescue inhaler bronchodilator usage. For COPD, it incorporated three questionnaires: the COPD Assessment Test (CAT), the Breathlessness, Cough and Sputum Scale (BCSS), and a Numerical Rating Scale (NRS). The CAT [54], recommended by the Global Initiative for Chronic Obstructive Lung Disease (GOLD) [55], contained eight items that measured the symptom impact of COPD on health status. The BCSS [56] recorded three items: the severity of breathlessness, cough and sputum. The NRS measured one item about the shortness of breath. Thus, the COPD diary consisted of a total of twelve items.

The diary interface presented one question per page with "*Back*" and "*Next*" buttons along with a progress bar. The questions used *RadioButton* or *Likert−Scale* styles for single-choice responses, in which users could change or deselect answers. If users tried to move on without answering, a popup message "*Please select one choice*" would appear (**Figure 2**). To ensure that they complete the clinical diary each day, a *TimePicker* [57] component was implemented to allow users to schedule a daily reminder. At the scheduled time, a notification would appear with the message "*Please complete the diary now!*" offering two buttons: "*Complete*" (to open the diary) and "*Dismiss*" (**Appendix I**).

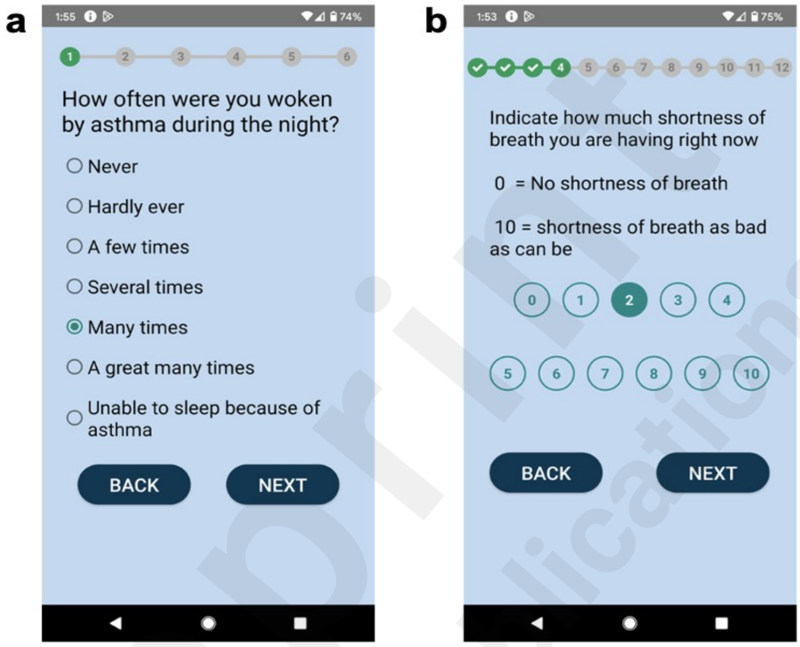


Figure 2. a) An ACQ question is presented in the asthma diary interface b) The NRS question is presented in the COPD diary interface.

Today Interface: Local Weather Information and Control Zone Results

The Today Interface featured both local weather information and the asthma/ COPD control zone of the day (**Figure 3a**). Since asthma or COPD symptoms can be impacted by air pollution, temperature, and humidity [58], the interface incorporated key air quality indicators outlined by the World Health Organization (WHO) guidelines, including participle matter (PM), ozone (O3), sulphur dioxide (SO2), and nitrogen dioxide (NO2) [59]. In particular, PM 2.5 and PM 10 pose significant risks for lung inflammation and exacerbating asthma and COPD [60]. In Canada, Environment Canada’s Air Quality Health Index (AQHI) is used to convey the health impact of air quality. This AQHI information was retrieved and displayed on the Today interface [61].

Furthermore, healthcare providers often develop personalized action plans with asthma and COPD patients to manage and control their symptoms, especially during severe episodes [62]. The app emulated this approach by featuring control zones (Red, Yellow, and Green) with actionable recommendations for self-management. {Education, 2007 #131}The zone results were generated based on clinical diary inputs and established clinical standards.

In addition, the BLE communication feature was implemented to allow users to collect data from a target wearable device at a convenient time via a toggle button. The device battery was also tracked and displayed on the Today Interface.

Report Interface: Clinical Symptom Prediction

The Report interface (**Figure 3b**) featured a pie chart representing the breakdown of the symptoms. These numbers, for instance, could represent symptom data sourced from an external wearable device or body sensor via wireless BLE communication technology. The pie chart design highlighted the percentages of each symptom in different colors so that users could easily monitor their symptom status throughout the day.

Profile Interface: Account Information Management

The Profile interface (**Figure 3c**) allowed users to view the information they entered during the previous profile setup by clicking the corresponding texts or arrow icons. In addition, users could manage their accounts and update the diary schedule, as well as log out of their accounts by clicking the "*Logout*" button.

Help Interface: Support, Resources, and Data Privacy

The Help interface (**Figure 3d**) provided users with detailed information on the app's privacy policy and frequently asked questions (FAQs). The privacy policy, developed in line with the Personal Information Protection and Electronic Documents Act (PIPEDA) [63] and Quebec

Privacy Law [64], explained the type of data collected, as well as how it would be stored and used (**Appendix II**). The FAQs provided additional explanations on the development of asthma and COPD zone calculations and technical support (e.g., reset password procedure). It also included the research team's contact email for additional inquiries.

In addition, the Google Firebase Firestore database [65] used for app data storage is Health Insurance Portability and Accountability Act (HIPAA) [66] compliant. Google will strictly adhere to the US national standards to protect health information and data through the Business Associate Agreement (BAA). The privacy policy also included the BAA information.

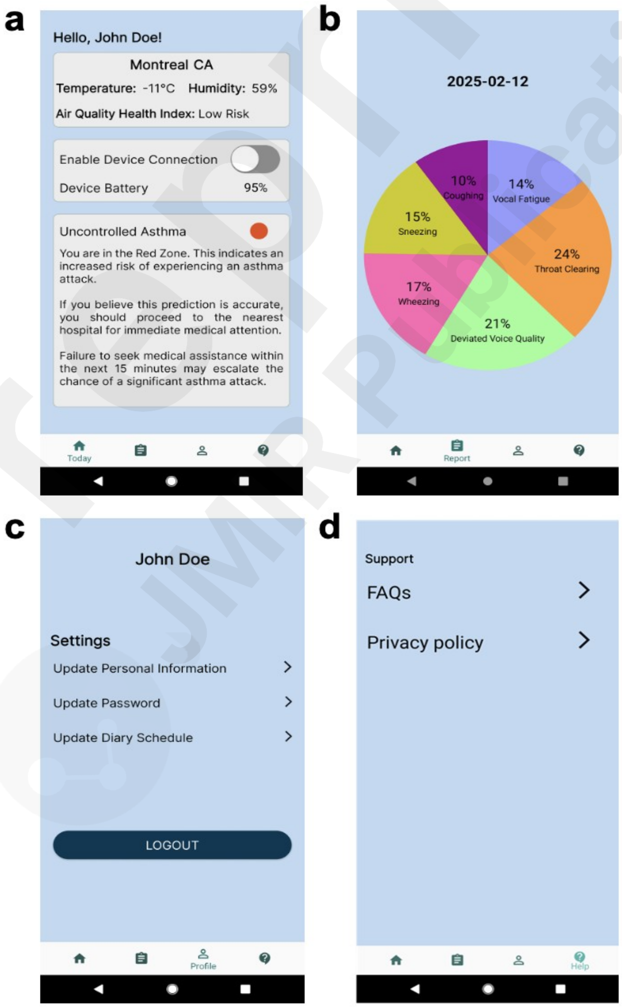


Figure 3. a) Today interface b) Report interface c) Profile interface d) Help interface.

Literacy Analysis for App Written Materials

To ensure clarity, the app's written materials, including the privacy policy, frequently asked questions (FAQ), the asthma action plan, and the COPD action plan, were evaluated using an open-source readability calculator, *Online-Utility.org* [67]. The target reading level was set to grade 9, matching most English-educated adults in the United States [68].

The Flesch Reading Ease Score was chosen to analyze the app content because it is a commonly used metric for evaluating the readability of research, education, and digital media content [69]. A Flesch Reading Ease Score between 70-80 is equivalent to a school grade of 7, 60-70 to grades 8-9, and 50-60 to grades 10-12 level [70]. The written materials of the app were iteratively revised to meet the target grade 9 level without compromising the information. The definitions of all metrics used in this study are summarized in **Appendix III**.

Mobile Accessibility Analysis for App Interfaces

Based on the World Wide Web Consortium guideline [71, 72] , the content of websites and applications needs to be accessible to people with disabilities and the general population. The Accessibility Scanner [73], the official Android accessibility testing tool available on the Google Play Store, was used to verify the accessibility of the app. The Scanner took a snapshot of the target interface and evaluated its components, such as content labels, target size, clickable items, and text and image contrast. The Scanner then provided content-based descriptions and recommendations for improvement. For example, one suggestion was to adjust the item’s height from 32dp to 48dp or larger.

Phase 2b: Backend Development

For backend development, the focus was to implement the app logic behind the screen as well as the data transmission between the app and the cloud database. The backend development was programmed using Java (version 11.0.12) [74] in Android Studio (Chipmunk 2021.2.1 version) [37] to implement (1) local weather data retrieval (2) asthma and COPD control zone calculations (3) cloud database storage and retrieval, and (4) BLE data transmission.

Local Weather Data Retrieval

The app retrieved the current local weather information (temperature and humidity) and used the current $PM_{2.5}$, O_3, and NO_2 to compute the AQHI. The information was displayed on the Today interface using the *OpenWeatherMap API* (One Call Version 3.0), an online service that provides the latest forecast data and air pollution information in over 200,000 cities for web and mobile app developers [75]. For example, developers have utilized the API in their Android apps, such as an app for improving older adults' fitness based on local weather conditions [76].

Control Zone Calculations and Generation of Action Plans

For asthma, the inputs for control zones (Red, Yellow, Green) included (1) user responses from the Asthma Control Questionnaire (ACQ) [52], (2) air quality data from the AQHI [61], as well as (3) the temperature and humidity levels of user's current city location. The ACQ provides a mean score determining asthma severity, while the AQHI indicates health risk levels, with high readings exacerbating symptoms [52, 77]. Extreme temperature and humidity can also trigger asthma symptoms [78]. Additionally, the app categorized asthma severity into "*Uncontrolled*," "*Partly Controlled*," and "*Well Controlled*" based on GINA guidelines, providing corresponding self-management action items from the Centers for Disease Control and Prevention (CDC) asthma action plan [79] (**Appendix IV**).

For COPD, the inputs for control zones (Red, Yellow, Green) included (1) user responses from the three validated questionnaires: the breathlessness, cough and sputum scale (BCSS) [56], the COPD Assessment Test (CAT) [54], and the numeric rating scale (NRS) [80], (2) air quality data from the AQHI, as well as (3) the temperature and humidity levels of user's current city location. These questionnaires assess the impact of COPD symptoms, which can be worsened by extreme temperature and humidity. Self-management action items for each control zone were provided based on the Canadian Thoracic Society (CTS) COPD action plan [81] (**Appendix IV**).

Cloud Database

mHealth apps often integrate cloud databases for data storage, processing, and sharing to ensure ease of access and scalability. In the *AIrway* app, Google Firebase Firestore [65] was used to store large volumes of real-time user data, such as account information and clinical diary responses. Firestore was considered an ideal cloud database for the app for three reasons.

First, Firestore provides real-time updates and integrates easily with web and mobile applications. Researchers have also employed Firestore in an eHealth management system for cardiovascular diseases [82] and a humidity and temperature monitoring system [83].

Second, while relational databases, such as SQL, require data to follow a pre-defined tabular schema, Firestore is a NoSQL (not only SQL) cloud database with no fixed schema. Firestore can store a large amount of data in collections and documents, where a collection can contain any number of documents, and each document can hold different types of data, such as strings, numbers, Booleans, arrays or objects, in the form of key-value pairs [84-86].

Lastly, NoSQL databases like Firestore offer horizontal scalability. When additional servers and virtual machines are needed, Firestore's capacity can be increased on demand without downtime. In contrast, SQL databases offer vertical scalability, which often requires upgrading existing infrastructure, such as CPUs and memory, to increase resources. This upgrade typically involves downtime, making the database temporarily unavailable for use [87].

BLE Communication

BLE data transmission is crucial because the app will receive data from an external wearable device, i.e., NSA in this study. BLE, developed by the Bluetooth Special Interest Group

Organization, is ideal for mobile health applications due to its low energy consumption, which allows small batteries to power devices like the NSA sensors [88, 89].

The BLE protocol stack [90] has two sections, namely controller and host, to enable the data transmission between a device and a mobile app. The controller is at the lower level of the stack that is implemented in hardware for radio wave transmission via an antenna. The link layer is responsible for the data connection between two devices, while the physical layer is responsible for analog communication operations [91].

The host operates at a higher level of the stack that defines the data transmission between devices, including mobile apps [92]. Two key concepts for BLE in mobile apps are the Attribute Protocol (ATT) and Generic Attribute Profile (GATT). The ATT defines a client-peripheral architecture where the client requests data from the peripheral and the peripheral responds [89]. The GATT uses ATT as its transport protocol and structures data hierarchically into services which group a collection of user data, known as characteristics [93]. For instance, to send device battery information to the app, a GATT battery service is set up containing a battery characteristic that represents the device's power level and can be read by the app [94].

Cloud Database Access Feature

To access Firestore, users must authenticate via the Firebase Authentication Service using credentials such as email and password, phone number, and third-party providers (e.g., Google and Facebook) [95]. In *AIrway*, the Register interface collected email and password inputs. Once the user input fields were filled, the *createUserWithEmailAndPassword* method [95] was used to create an account. Upon successful registration, the message "*User successfully created!*" was displayed, while a failure showed "*This account already exists. Please register another email!*" preventing users from moving to the next interface. The registered email and password then served as the user’s sign-in key for logging in and out of Firestore.

Cloud Database Password Reset Feature

Users could rest their passwords by clicking “*Forgot password? Click Here*” in the Login interface. This function utilized Firebase Authentication Service’s *sendPasswordResetEmail* method [96]. After entering a valid email in the Forgot password prompt, users received a reset link in the email. Clicking on the reset link allowed them to set a new password and update the account for subsequent logins.

Cloud Data Storage and Data Retrieval

Storing app data in Firestore involved three steps. First, read/write access was enabled by setting the rules to “*True*” for authenticated users. Second, in Android Studio, a storage path was defined with a collection named “*users*” and a document named after the UID generated during authentication. User data was written within this collection, with each user’s specific data stored in a separate document (**Figure 4**). Third, new data objects were added using the *Map<String,Object>¿* structure and *push* methods [97]. For example, an asthma diary question like “*How bad were your asthma symptoms when you woke up in the morning*?” was stored with the selected *RadioButton* response under the header “*Asthma Diary Response*.”

The app also retrieved user data, such as the account details in the Profile interface to enhance data visualization and increase user retention. This feature allowed users to quickly access personalized data and review previous entries before making updates. For example, when updating a password, the app reminded users of their current password to prevent them from setting the same one again. To achieve this dynamic data retrieval feature, the app first checked if the user document existed. If it did, the *getString* method [98] fetched the corresponding data in the app. The *setHint* method [99] then displayed the stored data.

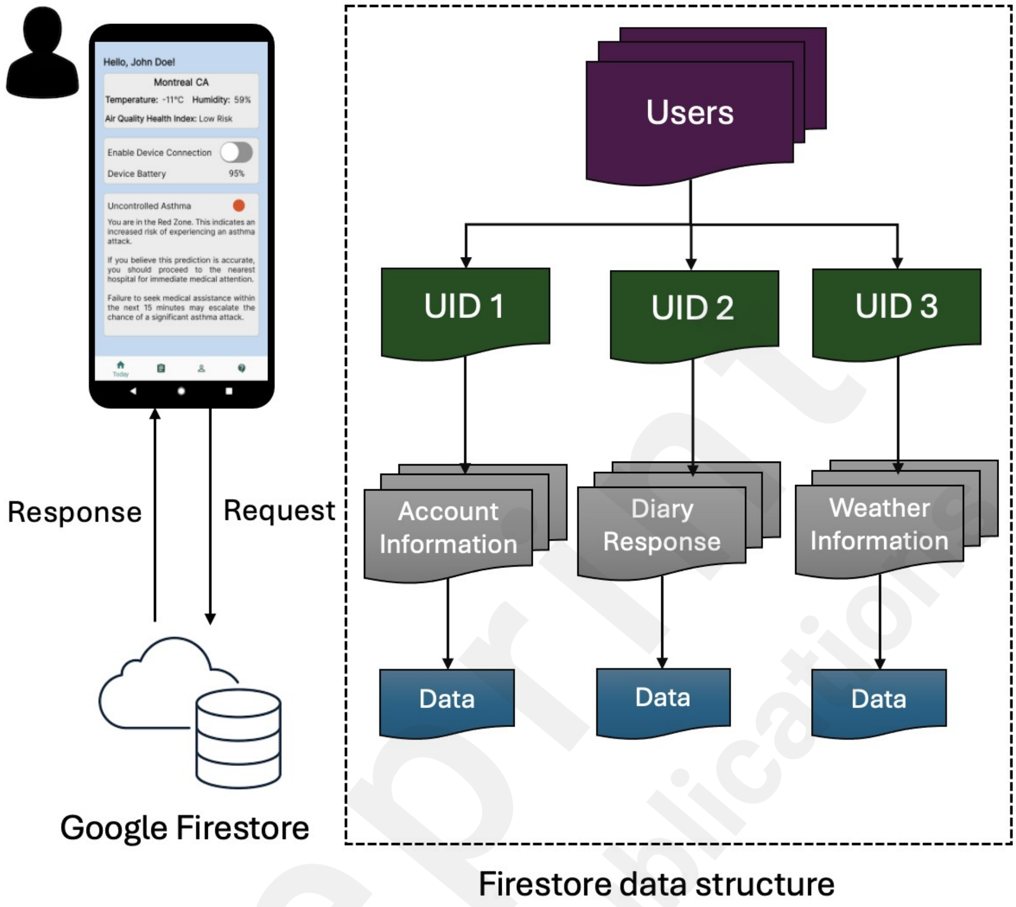


Figure 4. Firestore cloud architecture and data flow of *AIrway*.

BLE Scan, Connect, Read Features

The client and peripheral roles need to be defined for the BLE feature. In mobile app development, the app often acts as the client to initiate read or write operations, while surrounding BLE devices or sensors serve as the peripheral [100]. The *AIrway* leveraged the Android BLE API [101] to perform scanning, connecting, and reading functions.

The app provided a button for the user to initiate a scan for surrounding devices using the *BluetoothLeScanner* class [102]. Once the scan was complete, the app displayed a list of available devices, showing each device's name, Media Access Control (MAC) address (i.e., a hardware identifier that uniquely identifies each device), and its Received Signal Strength Indicator measured in dBm. After the user selected a target device, the app established a connection using the *connectGatt* method [103] and read the characteristics (i.e., numerical data) using the *readCharacteristic* method [104]. A real-time log view then displayed the characteristic values in real-time and users had the option to disconnect the connection as needed.

After receiving the characteristics, the app efficiently stored the information in Firestore. Specifically, the 16 bits of the characteristic were integrated into a larger 128-bit message with the first bit representing the actual value. To optimize storage, the app stored the first value in Firestore rather than the entire string of the characteristics.

BLE Experiment Setup

The final prototype's printed circuit board (PCB) was fabricated using the nRF5 series microcontroller. The nRF52840 Development Board [105] was used to simulate the data transfer, build a ready-to-use BLE protocol, and test the BLE data transmission with the app. Two services, namely, symptom event classification and battery level monitoring, were programmed using C programming language. This simulation advertised these two services to the app with a single characteristic:

- Classification: Since a machine learning algorithm will be deployed on the MCU for symptom classification based on probabilities (e.g., coughing – 87%, wheezing – 3%, and sneezing – 10%), each symptom will be labelled with an integer (e.g., 1 = cough, 2 = talking, 3 = breathing). For simulation purposes, the MCU was programmed to send random integers from 0 to 5 every 500 milliseconds.
- Battery Level: The MCU sent the battery level as an integer ranging from 0 to 100 to the app. Upon connection, the device sent an initial value of 100, which decremented by 1 every two seconds and reset once it reached 0.

Phase 3: Functionality Usability Tests with Technical Raters

A pilot usability study with technical raters (app developers) was performed to evaluate the app's pilot functionality. This study was approved by the Institute of Review Board of the Faculty of Medicine and Health Sciences at McGill University under protocol number A12-E39-22B.

Implementation of App Usability Survey

The User Version of the Mobile Application Rating Scale (uMARS) [106] and IQVIA [107] were used. These tools provide overall scores on the app's usability, functionality, aesthetics, content, and legal aspects.

The uMARS questionnaire, widely used for evaluating mHealth apps [106], is structured into five sections: engagement, functionality, aesthetics, information quality and subjective quality. For our study, the original uMARS questionnaire was modified for clarity and to ensure its relevance to the specific functions of the app (**Appendix V**). An open-text question was added at the end of each section to enable technical raters to provide additional feedback.

In addition, the IQVIA questionnaire was used to assess the presence of specific app functions, with a particular focus on self-management features such as alerts, guidance, and communication [107] (**Appendix VI**). Previous studies [107, 108] have utilized both the uMARS and IQVIA questionnaires to better assess mHealth apps targeting self-management purposes.

The usability survey was deployed using McGill's IT-managed *LimeSurvey* platform (version 3) [109] and contained 51 items in total. The survey included pre-screening (5 items), consent (1 item) and four separate sections. Sections A and B measured technical raters' demographics (6 items) and mobile app development experience (5 items). Section C included the uMARS questionnaire (23 items), while Section D included the IQVIA questionnaire (11 items).

Study Recruitment and Procedure

A convenient sample of app developers was recruited via an electronic advertisement that was disseminated through McGill and other Canadian universities' Computer Science student mailing lists and social media. Interested participants received a pre-screening email from a student coordinator, and those who met the criteria were scheduled for a 1.5-hour Zoom session.

Inclusion criteria were: (i) over the age of 18; (ii) at least one year of mobile app development experience or, for Computer Science Ph.D. students and post-doctoral fellows, completion of a mobile app development course or related thesis research; (iii) Android smartphone user with internet access; and (iv) use of English as the primary daily language. Exclusion criteria included severe cognitive and/ or psychiatric conditions that may prevent study completion. Technical raters were compensated with a $50 CAD Amazon gift card.

During the Zoom session, a study investigator explained the workflow. The raters received a fictitious Gmail address to access an instruction manual with step-by-step tasks. After completing pre-screening, consent, demographics, and mobile app development sections in *LimeSurvey*, they received an email from Firebase App Distribution [110] to download the app. Once the tasks were completed, they filled out the uMARS and IQVIA questionnaires in *LimeSurvey*.

Results

Verification of mHealth Apps Development Standards

Overall, *AIrway* demonstrated excellence in implementing seven of the eight best practices for mHealth app development [35]. The app addressed usability, privacy, security, appropriateness, transparency, safety, and technical support. The technology criterion, however, requires further refinement to achieve full compliance with industry standards (**Table 4**).

For usability compliance, we conducted a usability evaluation with technical experts, incorporated clear instructional interfaces, and adhered to Android design guidelines throughout the user experience development process. As the app targeted English-speaking adults with respiratory conditions, multilingual support was deemed unnecessary for the initial implementation.

Privacy requirements were addressed through a comprehensive policy framework that outlines the terms of use, data collection protocols, and secure cloud storage procedures. This framework ensures the protection of sensitive patient information and compliance with relevant regulations. Given *AIrway*'s focus on adult users, protocols for minor protection were intentionally excluded, as they are not applicable to the target demographic.

Security was achieved through Google Firestore, a cloud service with access restricted to password-protected accounts exclusive to the research team. Nonetheless, potential cybersecurity threats remain unaddressed. The usability study confirmed the criteria for appropriateness and suitability by defining the target user demographic and evaluating the app's technical performance.

Transparency requirements were satisfied through dedicated Help and FAQ sections providing author credentials, mission statements, funding information, and scientific evidence supporting the asthma and COPD control zone calculations. Safety protocols included explicit disclaimers regarding clinical diagnosis limitations and emergency response guidance for users experiencing severe symptoms.

Technical support was implemented through monitored email channels, with application updates distributed via Firebase App Distribution rather than automatic update deployment. Although the technology criterion was partially fulfilled by supporting multiple data structures and ensuring proper functionality, it requires improvement in cross-platform compatibility and offline accessibility, as the current implementation is Android-specific and requires continuous internet connectivity for cloud service access.

Table 4. AIrway against established mHealth development standards and guidelines [35]. Y=Yes, N=No, and NA=Not Applicable.

Usability criterion	***AIrway***
The app has been tested by potential users before being made available to the public.	Y (Usability study)
It has instructions or some kind of assistance for use.	Y (Help page)
It is easy to use (i.e., navigation is intuitive).	Y (Usability study)
It follows the recommendations, patterns, and directives in the official manuals of the different operating systems (Android, iOS, or others).	Y (Android development guidelines)
The interface design follows the same pattern. That is, all graphic elements (typographies, icons, and buttons) have a consistent appearance. The function of each element (navigation menu, lists, and photo gallery) is clearly identified.	Y
The functionality is adapted to the purpose of the app.	Y
The information of the app must be able to be accessed in the shortest possible time. All users must be able to access all resources regardless of their capabilities.	Y
The app can be consulted in more than one language. All languages adapt appropriately to the content interface.	NA
Privacy criterion	
The app gives information about the terms and conditions of purchases in the app and personal data recorded.	Y
It gives information about the kind of user data to be collected and the reason (the app must only ask for user data that is essential for the app to operate). It gives information about access policies and data treatment and ensures the right of access to recorded information. It describes the maintenance policy and the data erasure procedure. It gives information about possible commercial agreements with third parties.	Y (Consent form/ privacy policy)
It guarantees the privacy of the information recorded. It requires users to give their express consent. It warns of the risks of using the app.	Y (Privacy policy)
It tells users when it accesses other resources of the device, such as their accounts or their social network profile.	NA
It takes measures to protect minors in accordance with the current legislation.	NA
Confidential user data are protected and anonymized, and there is a privacy mechanism so that users can control their data.	Y (Anonymized ID/ fictitious names)
Security criterion	
The app has encryption mechanisms for storing, collecting, and	Y (Password protection in

exchanging information. It has password management mechanisms.	the cloud)
The cloud services used have the relevant security measures. It states the terms and conditions of cloud services.	Y (Firestore cloud terms/conditions)
The authorization and authentication mechanisms protect the users' credentials and give access to their data. It limits access to data that is only necessary for the user.	Y (Firestore account credentials/ login)
It detects and identifies cybersecurity vulnerabilities, possible threats, and the risk of being exploited. It applies the appropriate security measures to cybersecurity vulnerabilities in the face of possible threats.	NA
Appropriateness and suitability criteria	
The end users for whom the app is designed are explicitly indicated or actually intuitable (the name identifies the app) to the audience to whom it is set out.	Y
The benefits and advantages of using the app are explained.	Y
The app has been validated or created by experts (e.g., a group of specialized professionals, a health organization, or a scientific society).	Partially Y (Usability study with developers)
Transparency and content criteria	
The app identifies the authors of the content and their professional qualifications.	Y (Help page/FAQ)
It gives transparent information about the owners' identity and location.	Y (Help page/FAQ)
It gives information about its sources of funding, promotion and sponsorship, and possible conflicts of interest. Any third parties or organizations who have contributed to the app development are clearly identified.	Y (Help page/FAQ)
It uses scientific evidence to guarantee the quality of the content. It is based on ethical principles and values.	Y
The sources of the information are indicated. Concise information is given about the procedure used to select the content.	Y
Safety criterion	
The possible risks to users are identified. Users are warned that the app does not intend to replace the services provided by a professional.	Y (Action plan)
Potential risks for users caused by bad usage or possible adverse effects are explained.	Y
Technical support and updates criteria	
It gives a warning if updates modify or affect how the app functions. It gives a warning if updates can influence insensitive data.	Y (Firebase App Distribution can send updates)
Frequent security updates are guaranteed. Every time an update of a third-party component is published, the change is inspected,	Y (same as above)

and the risk evaluated.	
The frequency with which the content of the app is revised or updated	Y (same as above)
Users have support mechanisms (email, phone, and contact form) for solving doubts, problems, or issues related to the health content, and technical support.	Y
Technology criterion	
It works correctly. It does not fail during use (e.g., blocks). Functions are correctly retrieved after context changes (e.g., switch to another app and return), external interruptions (e.g., incoming calls or messages), and switching off the terminal.	Y
It does not waste resources excessively: battery, central processing unit, memory, data, or network.	Partially Y (battery usage with BLE, memory usage)
It can work in flight mode and deal with network delays and any loss of connection.	N (Need internet to log in and connect to the cloud)
It supports multiple versions of data structures	Y (Graph, text, and button)
It supports multiple formats (e.g., to support different operating systems).	N (Android only)

Verification of Literacy Analysis

Based on the readability calculator [67], the Flesch Reading Ease score for the privacy policy, frequently asked questions (FAQ), the asthma action plan, and the COPD action plan were 58.63, 56.69, 57.72, and 59.91, respectively. With an average score near 60, these materials are accessible to users with a formal education level of grades 9-10.

In addition to the Flesch Reading Ease Score [111], five other readability assessments were conducted. The Gunning Fog Index [112] indicated an 8th to 10th grade reading level, while the Coleman Liau Index [113] suggested suitability for a 7th to 10th grade audience. The Flesch–Kincaid Grade level [114] indicated a 6th to 8th grade range, and the Automated Readability Index (ARI) [70] estimated a 5th to 7th grade level. The SMOG (Simple Measure of Gobbledygook) index measured the texts based on syllables [115] and concluded that the materials were suitable for a 9th to 10th grade audience. Literary analysis results are summarized in **Table 5**.

Table 5. Literacy analysis on *AIrway* app materials [116].

Readability metrics	Privacy policy	FAQ	Asthma action plan	COPD action plan	Interpretation of the metric
Gunning Fog Index	8.97	9.38	8.44	8.49	8th – 10th grade
Coleman Liau Index	9.18	9.39	7.47	8.35	7th –10th grade
Flesch–Kincaid Grade level	7.57	8.03	7.17	6.80	6th – 8th grade
ARI (Automated Readability Index)	5.94	6.33	4.86	5.38	5th -7th grade
SMOG Index	9.32	9.67	9.06	9.71	9th – 10th grade

Accessibility Results

The accessibility results based on the Accessibility Scanner are summarized in **Appendix VII**. Based on this analysis, three primary areas are identified for further enhancing the app's user interfaces. First, it recommended modifying the width layout of test view components from a fixed value to an adjustable parameter, such as $wrap_{content}$. This modification enabled dynamic text expansion, which could prevent component overlap when screen sizes change. Second, it suggested increasing the text size of input items from the current range of 24dp – 44dp to a minimum of 48dp for better readability. Lastly, it recommended enhancing the contrast colors of the "*Today*," "*Report*," "*Profile*," and "*Help*" icons to achieve a minimum ratio of 3.00:1 as well as the contrast of unselected time-scrolling texts within the Diary Reminder interface to at least 4.50:1 with respect to the background.

BLE Experiment Results

The BLE experiment evaluated data transmission between *AIrway* (client) and the nRF52840 development board (peripheral). First, the app's scan feature accurately detected the board by its device name, "*NSA BLE*," along with the unique manufacturing MAC address ($D5:D2:5D:62:AF:48$). Signal strength, measured in decibel-milliwatts (dBm) on a logarithmic scale (with values closer to 0 dBm indicating stronger signals [117]), showed that the board was advertising the highest signal value of -19 dBm among the neighbouring BLE devices, which confirmed its closest proximity to the app. The results are summarized in **Table 6**.

Table 6. A summary of BLE experiment result.

Scan range	Corresponding MAC address
-94 dBm	1E:73:99:6D:30:E7
-19 dBm	D5:D2:5D:62:AF:4B
-100 dBm	57:97:8B:22:DC:5F
-86 dBm	5B:7B:F2:E7:2C:3C
-81 dBm	6F:AE:90:EE:00:95
Data transmission timestamp	**Read characteristics**
May 18, 16:33:28	0x0D (equivalent to integer 13)
May 18, 16:33:29	0x0D
May 18, 16:33:30	0x0C (equivalent to integer 12)
May 18, 16:33:31	0x0C
May 18, 16:33:32	0x0B (equivalent to integer 11)

Once connected, the data read characteristic feature was successfully displayed and verified visually. As described in the experiment setup, simulated battery level data was transmitted using random integers and set to decrement by 1 every two seconds. The app accurately retrieved the real-time data timestamp along with the corresponding hexadecimal data value (e.g., 0x0D representing integer 13, followed by 0x0C representing integer 12 after two seconds). This result confirmed the successful integration of the scan, connect, and read characteristic features.

Furthermore, physical distance, connection time, and obstacles were found to impact BLE performance (**Table 7**). The best performance for stable and continuous data streaming occurred when the devices were adjacent without obstacles. However, after connections exceeded 10 minutes, some packet loss was observed. Additionally, occasional disconnections, particularly when they were farther apart, were likely due to interference from nearby BLE devices. In these cases, the app was able to manually reconnect to the board.

Table 7. BLE performance test summary.

Task	Physical Distance	Scan Signal Strength	Run Time (hours: minutes: seconds)	Obstacle
Put the board next to the phone for 5 minutes	0	-26dBm	14:37:35 – 14:42:37 pm	None
Trial 1: Put the board next to the phone for 10 minutes Trial 2: Put the board next to the phone for 10 minutes	0	-26dBm	Trial 1: 16:23:50 – 16:29:19 pm (self-disconnected) Trial 2: 15:40:18 – 15:51:10 pm	None
Put the board next to the phone for 20 minutes	0	-26dBm	14:01:37 – 14:20:07 pm	None
Put the board next to the phone for 30 minutes	0	-26dBm	15:10:17 – 15:42:09 pm	None
Put the board next to the phone for 40 minutes	0	-26dBm	13:13:23 – 13:53:11 pm	None
Put the board and the phone on two different lab tables for 5 minutes	~2m apart	-70dBm	14:50:24 – 14:52:49 pm (self-disconnected)	None
Put the board on the lab table and the phone outside the lab for 5 minutes	~4m apart	-91dBm	13:47:24 – 13:48:13 pm (self-disconnected)	Door
Put the board and the phone next to a microwave (off) for 5 minutes	~0.6m apart	-58dBm	14:49:44 – 14:55:01 pm	Microwave
Put the board and the phone next to a microwave (on) for 1 minutes	~0.6m apart	-58dBm	15:00:14 – 15:01:31 pm	Microwave

App Usability Evaluation

A total of five app developers were recruited and participated in the evaluation of *AIrway* usability. Most technical raters were female, identified as visible minorities, and resided in Canada. They held at least a bachelor’s degree, worked part-time, and had an average age of 29.0 years. The majority were Computer Science Ph.D. students or post-doctoral fellows with 1-2 years of Android mobile app development experience and each had developed at least one app before (**Table 8**).

Table 8. Demographics and mobile app development experience of technical raters.

Variable	**Category**	**n (%)**
Gender identity	Male	2 (40)
	Female	3 (60)
	Prefer not to answer	0
Visible minority status	Yes	4 (80)
	No	0
	I prefer not to answer	1 (20)
Reside location	United States	0
	Canada	5 (100)
Education level	High school diploma	0
	Apprenticeship or trades certificate/diploma	0
	College or CEGEP degree/diploma, or university degree lower than bachelor’s	1 (20)
	Bachelor’s degree	20 (20)
	Graduate degree (master’s or doctorate)	3 (60)
Job Status	Full-time (>30 hours per week) employed	3 (60)
	Part-time (<30 hours per week) employed	2 (40)
	Self-employed	0
	Unemployed	0
Age	Mean	29.0 (years)
	SD	5.61 (years)
Primary role	Designing products (e.g., UI designer, interaction designer)	0
	Developing software (e.g., programmer, developer, software engineer)	1 (20)
	Testing software (e.g., tester, quality analyst)	0
	Managing software development (e.g., project manager, IT manager)	1 (20)
	Computer Science Ph.D. student/ post-doctoral fellow	2 (40)
	Other: Software and Hardware Support Analyst	1 (20)
Years of experience in mobile development	1-2 years	5 (100)

	2-3 years	0
	3-4 years	0
	More than 5 years	0
Mobile app development platforms (multiple selected)	iOS	2
	Android	5
	Windows	2
	BlackBerry	0
Numbers of app(s) developed	1 app	4 (80)
	2-5apps	1 (20)
	More than 5 apps	0
Size of the mobile app development team in the organization	1-9 employees	3 (60)
	10-99 employees	1 (20)
	100-999 employees	0
	1,000-9,999 employees	0
	10,000+ employees	0
	Not applicable	1 (20)

uMARS Results

The overall mean uMARS score for *AIrway* was 3.6 out of 5.0 (SD = 0.2), indicating above-average quality (>3.0) (**Figure 5a**). This score was based on assessments of engagement, functionality, aesthetics, information quality and subjective quality.

The information quality section received the highest mean score of 4.4 out of 5.0 (SD = 0.2), which implied that the app's quality and visual information were highly appealing to users. Similarly, the functionality section also received the highest mean score of 4.2 out of 5.0 (SD = 0.4), which indicated excellent performance, ease of use, navigation, and gestural design for the app. The aesthetics section received a mean score of 3.5 out of 5.0 (SD = 0.6), while the engagement section received a mean score of 3.4 out of 5.0 (SD = 0.4). Both the aesthetics and engagement sections indicated appropriate layout elements and customization aspects. Among all the sections, the subjective quality section received a score of 2.6 out of 5.0 (SD = 0.3), which indicated a moderate willingness to use the app in the next 12 months and pay for its usage.

IQVIA Results

The IQVIA functionality score ranged from 6 to 11, with a median of 8 (**Figure 5b**). All technical raters confirmed that the app included recording, data collection, intervention, display, and alert functions (100%). Most agreed (80%) that the user data could be evaluated by others, and over half (60%) expressed that the app supported instructing, guiding, and sharing data functions. However, only one rater (20%) observed a communication feature that allowed users to interact with others via social networks and provided information in a variety of formats (e.g., text, photo, video).

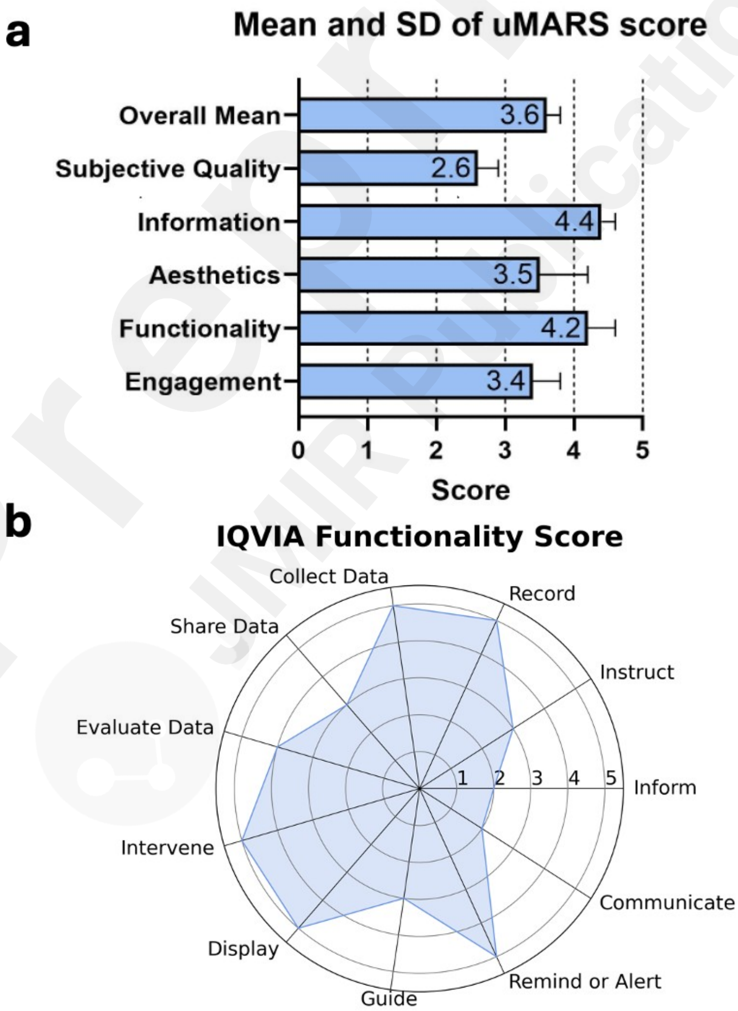


Figure 5. a) Technical raters' means and standard deviations (SD) of uMARS, and b) technical raters' IQVIA functionality scores (N=5).

Open-ended Feedback from Technical Raters

Feedback was collected through five open-ended questions regarding the app's engagement, functionality, aesthetics, information quality, and potential improvements. Overall, the technical raters expressed positive impressions of the app and a clear understanding of its purpose. The results are summarized in **Appendix VIII**. A key suggestion was to add an option to show and hide passwords in the "*Enter a password*" and "*Retype Your Password*" fields on the Register interface, which would help users verify that their passwords match.

Discussion

This research study presented a systematic methodological development of *AIrway*, a purpose-built digital health solution for managing asthma and COPD. Our approach aimed to combine rigorous academic standards with industry best practices throughout the app's development lifecycle. To ensure broad accessibility, the app's content – including the privacy policy, FAQ, and action plan – was written at a 9^{th} to 10^{th} grade reading level, ensuring it is comprehensible to both general and geriatric users. An accessibility review of the user interfaces recommended specific enhancements, including adjusting layout widths to accommodate dynamic text and increasing text sizes to a minimum of 48dp. These recommendations will be implemented and tested across various Android devices in future iterations to ensure optimal content presentation.

BLE connectivity testing confirmed robust real-time communication with the nRF52840 Development Board, accurately interpreting hexadecimal values. These results support future integration with NSA wearables utilizing nRF5 series microcontrollers. However, performance tests revealed that distance, connection time, and obstacles affect BLE stability. Future app development will prioritize optimizing critical parameters like the maximum transmission unit (MTU) and transmission frequency, while implementing auto-reconnection functionality to minimize packet loss.

In the usability evaluation, *AIrway* scored 3.6/5.0 on the uMARS, reflecting high user satisfaction and a median IQVIA functionality score of 8/11, confirming its efficacy in self-management support. These results were compared favorably with commercial mHealth apps for respiratory, cardiac, and sleep disorders, which typically report scores ranging from 3.0–4.2 on MARS and 6–10 on IQVIA [107, 108, 118, 119]. Although *AIrway* performed well in most design principles, the lower uMARS subjective quality score (2.6/5.0) indicated areas for enhancement. Technical raters valued *AIrway*'s utility for condition management but showed limited interest in long-term use or payment. This outcome was anticipated, given that *AIrway*'s features, such as clinical diaries and medication reminders, were tailored for patients with respiratory conditions rather than technical evaluators. Future efforts will focus on clinical validation studies with asthma and COPD patients to obtain targeted feedback aligned with the app's intended users.

The usability study was limited by a relatively small sample size (N=5) compared to the 15–40 participants typically included in similar research [120-122]. This sampling limitation was attributed to recruitment challenges through university mailing lists and paid research groups on Facebook, which did not effectively reach the intended audience. While some individuals expressed initial interest, they failed to meet all inclusion criteria following pre-screening procedures. Also, the usability evaluation relied on subjective uMARS and IQVIA ratings, which are prone to perception variability and bias. A more comprehensive assessment could incorporate objective usage metrics such as system interaction patterns (e.g., login frequency, session duration), error occurrence rates, feature utilization statistics and configuration preferences to provide a more accurate view of user experiences and app performance.

Currently, *AIrway* is Android-specific, but future development efforts could explore cross-platform frameworks like Flutter [123]. By leveraging similar package structures, the existing Android Java codebase could be converted to Flutter Dart code to create a cross-platform version. This expansion would significantly improve accessibility and equity by extending availability to a broader user base. Above all, a comprehensive clinical study with asthma and COPD patients is critical to provide invaluable direct end-user feedback, allowing for more targeted refinements that address the specific needs and preferences of *AIrway*'s intended user populations.

Acknowledgements

This study was supported by the Fonds de Recherche du Québec - Santé (#322737), National Institute on Deafness and Other Communication Disorders (R01 DC021461), the Centre for Research on Brain, Language Incubator Award and Canada Research Chair research stipend (N.Y.K.L.-J.). This work was in part supported by Bavarian State Ministry of Science and the Arts (A.M.K.). The presented content is solely the responsibility of the authors and does not necessarily represent the official views of the above funding agencies. The authors would also like to thank Meghana Munipalle for her assistance in figure generation.

Data Availability

The materials, including the data and the app code, can be accessed upon request to the authors.

Conflict of Interest

The authors declared that they have no conflict of interest.

Author Contributions

Andrew Chao: Conceptualization, Software, Investigation, Formal Analysis, Visualization, Writing-original draft, Writing-reviewing and editing.

Lisa Martignetti: Project Administration, Writing-reviewing and editing.

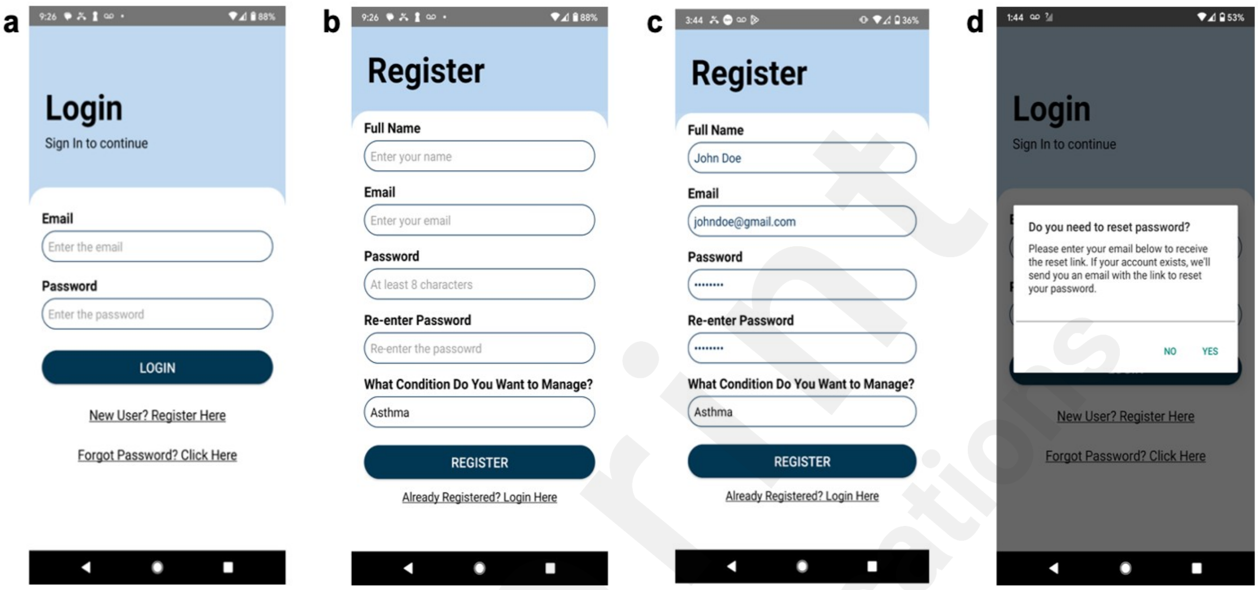
René Groh: Conceptualization, Software, Writing-reviewing and editing.

Andreas M. Kist: Conceptualization, Funding Acquisition, Writing-reviewing and editing.

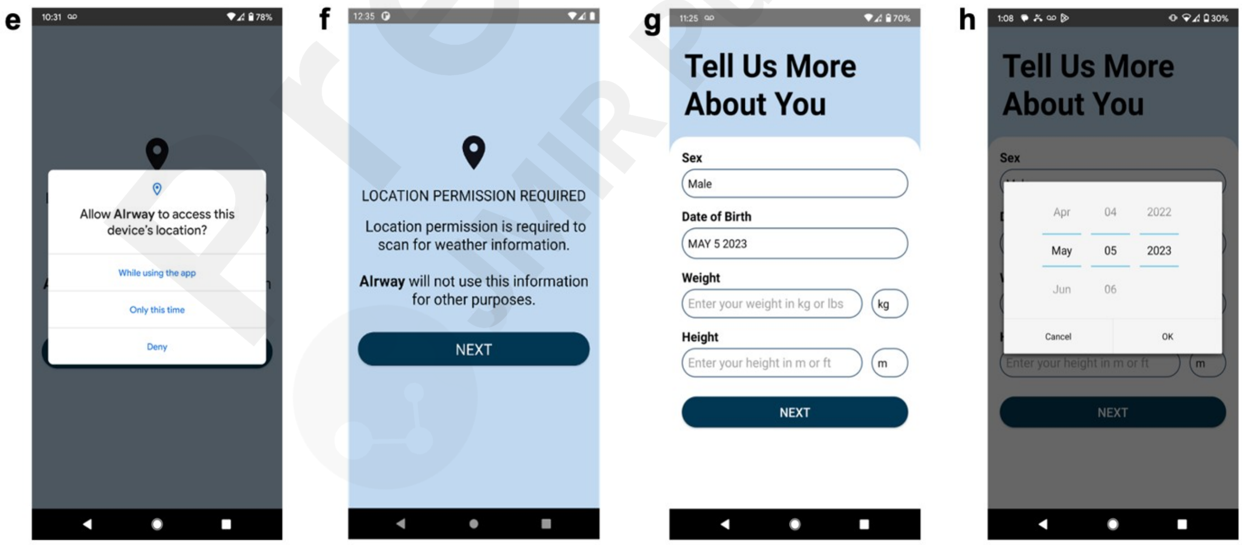
Nicole Li-Jessen: Conceptualization, Visualization, Supervision, Resources, Funding Acquisition, Project Administration, Writing-original draft, Writing-reviewing and editing.

Appendices

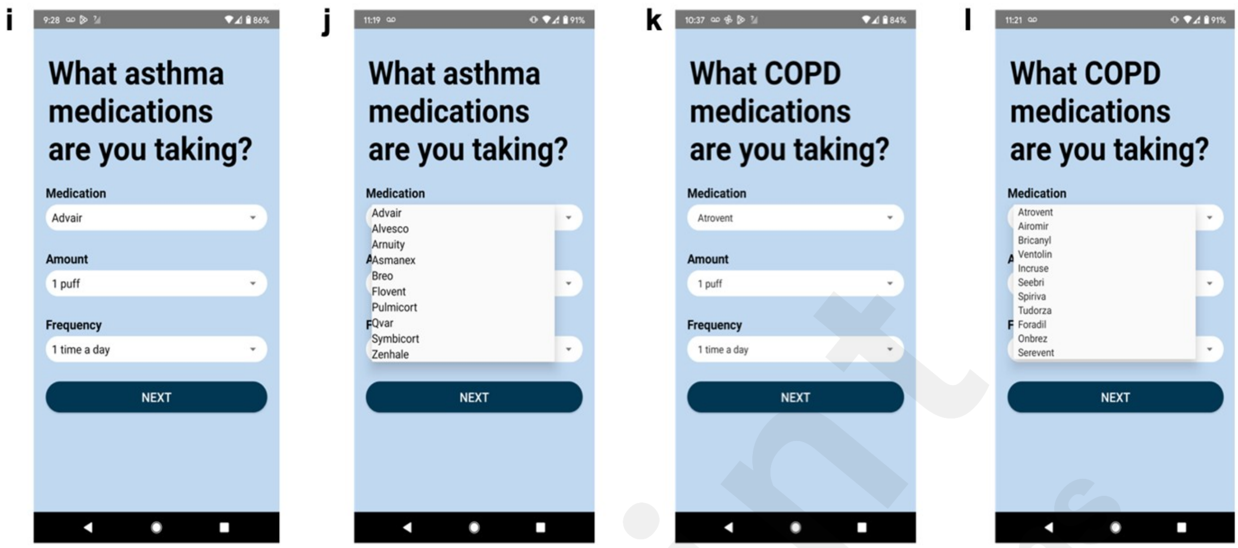
Appendix I: App Interfaces



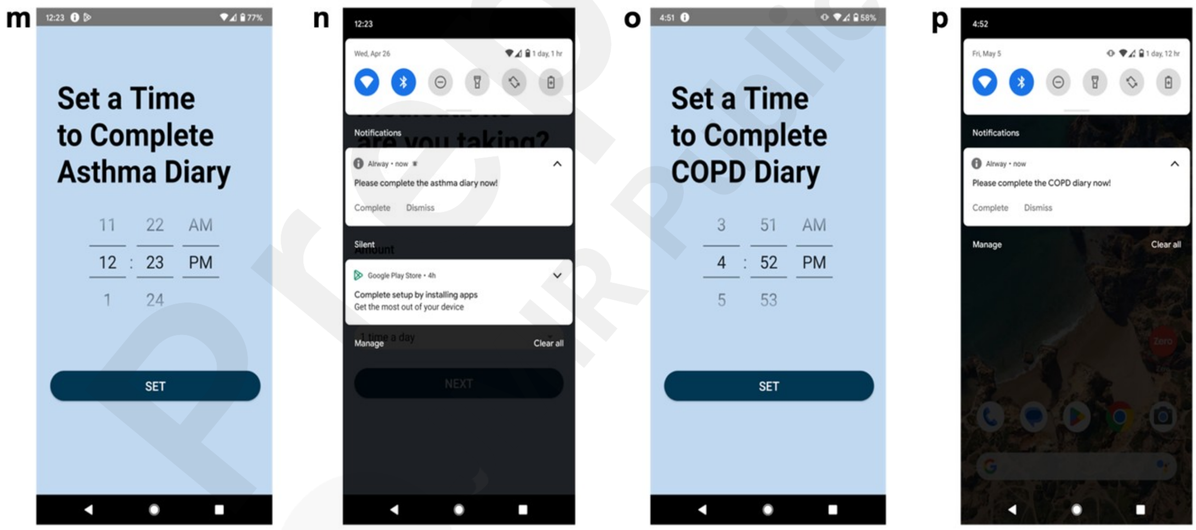
a) Login interface b) Register interface c) Register interface with filled information d) Forgot password prompt.



e) Location permission prompt f) Location permission interface g) Account information interface h) DataPicker selection



i) Asthma medication interface j) Asthma medication drop-down menu example k) COPD medication interface l) COPD medication drop-down menu example.



m) Asthma time setting interface n) Asthma diary notification o) COPD time setting interface p) COPD diary notification.

Appendix II: Privacy Policy for the App

To create a user account in the app, we require some information about you. The information is used to personalize the user experience when using the app. For the purpose of this study, you will enter fictitious data.

The following items will be collected and displayed on the Profile page and will only be visible to you (fictitious data):

- Name
- Email address
- Date of Birth
- Sex
- Weight
- Height
- Medication (usage, dose, frequency)

After logging in, you will also be asked to enable location permission for weather information. The geolocation of the device will be used to display the proper weather information. The following weather information will be displayed on the Today page:

- City name
- Temperature
- Humidity
- AQHI

The following items will be collected and displayed on the Report page

- Your predicted airway conditions
- Your asthma diary response
- Your COPD diary response

Google Firebase services:
Our app uses Google services in order to provide you the cloud functions, such as authentication and data storage. During the use of Google cloud, the following data is collected by Google, extracted from the Google cloud service: https://firebase.google.com/support/privacy/

Firebase Service	Firebase Authentication
Data required	Passwords, emails, user agents, IP address
How is it used to provide the service	Firebase Authentication uses the data to enable end-user authentication and facilitate end-user account management. It also uses user-agent strings and IP addresses to provide added security and prevent abuse during sign-up and authentication.
Retention	Firebase Authentication keeps logged IP addresses for a few weeks. It retains other authentication information until the Firebase customer initiates deletion of the associated user, after which data is removed from live and backup systems within 180 days.

Firebase Service	Firebase App Distribution

Data required	Firebase installation IDs, secure Android IDs, emails
How is it used to provide the service	Firebase App Distribution uses the data to distribute app builds to testers, monitor tester activity, and associate data with tester devices.
Retention	Firebase App Distribution retains user information until the Firebase customer requests its deletion, after which data is removed from live and backup systems within 180 days.

Note that Google will collect and retain your IP address, among other user information, until the deletion of the account, which is a common practice for using third-party cloud services. As such, we will export all collected app data from the cloud and request the deletion of the account at the end of the study. Once the account is closed, your information will be deleted from the Google backup system within 180 days.

How do we use the information?
We do not use any of your personal information for any reason other than to provide you with the services through the app, including:

1. Registering your user account and allow you to manage the user profile
2. Providing the prediction results
3. Performing statistical analysis about the usability of the app

Who will have access to the information?
All information collected during this study will only be accessible to the researchers at the Voice and Upper Airway Research Lab, McGill University, Canada.

Where do we store the information?
We will temporarily store the information in the Google Firebase Firestore cloud database during the study. After the study, we will export the data and request the deletion of the cloud. The data will then be completely anonymized (destroyed key) and stored safely on password-protected computers to which only the research team has access.

How long do we store the information?
Data will be collected electronically and stored for 7 years following the completion of the study. After this time, all digital files will be destroyed.

How can I revoke my consent or have my information deleted?
To revoke consent and/or have information deleted, please contact support at voicelab.mcgill@gmail.com

Appendix III: Readability metrics and definition

Readability Metrics[69]	Interpretation
Flesch–Kincaid Grade level	The Flesch-Kincaid grade level is the most widely used measures of readability. It is used by the United States military to evaluate the readability of their manuals. It is equivalent to the US grade level of education.
Flesch Reading Ease Score	A score between 1 and 100, with 100 being the highest readability score. Scoring between 70 to 80 is equivalent to school grade level 8, which means text should be fairly easy for the average adult to read. Both Flesch use total words and sentences.
Gunning Fog Index	Generates a grade level between 0 and 20. It estimates the education level required to understand the text. A Gunning Fog score of 6 is easily readable for sixth graders. Texts aimed at the public should aim for a grade level of around 8. Texts above 17 are for the graduate level. GF uses total words and sentences and helps reduces complexity and help researchers write papers.
Coleman Liau Index	Instead of syllables per word and sentence lengths, the Coleman Liau Index relies on characters and uses computerized assessments to understand characters more easily and accurately. Mostly used in school. A score of 6 is 6th grade in the US schooling system. If the writing texts are for the public, aim for a grade level of around 8-10.
ARI (Automated Readability Index)	The U.S. grade level required to read a piece of text. In some ways, it is similar to other formulas. Its difference is rather than counting syllables, it counts characters. The more characters, the harder the word.
SMOG Index	Measures how many years of education the average person needs to have to understand a text. It is best for texts of 30 sentences or more.

Appendix IV: Summary of zone calculation and action plan in *AIrway*

Summary of asthma zone calculation and action plan in *AIrway*.

Zone	Thresholds	Asthma action plan
Red	"Uncontrolled" • Three times or more a week with daytime symptoms and nocturnal symptoms OR • One per week with exacerbation OR • ACQ score > 1.5 OR • Temperature < -12.2°C or > 49 °C OR • Humidity < 30% or > 75 % OR • AQHI > 7	• A message to user: "You are in the Red Zone. This indicates an increased risk of experiencing an asthma attack. If you believe this prediction is accurate, you should proceed to the nearest hospital for immediate medical attention. Failure to seek medical assistance within the next 15 minutes may escalate the likelihood of a significant asthma attack."
Yellow	"Partly Controlled" • More than twice a week with daytime symptoms OR • Any nocturnal symptoms OR • One per year with exacerbation OR • ACQ score between 0.75 -1.5	• A message to user: "You are in the Yellow Zone. If you believe this prediction is accurate, you should incorporate prescribed medications into your routine as directed by your healthcare provider. Please pay attention to the temperature, humidity, and pollen levels in your area. If you do not return to the Green Zone after an hour, it is advisable to contact your doctor

		before considering oral steroids."
Green	"Well Controlled" • No (less than twice a week) daytime symptoms OR • No nocturnal symptoms, exacerbations OR • ACQ score <= 0.75	• A message to user: "You are in the Green Zone. It's important to maintain this status. If you believe this prediction is accurate, you should continue taking your medication as prescribed, even if you are not experiencing any symptoms. Additionally, be proactive in avoiding triggers that may worsen your condition. Consistent adherence to your treatment plan and preventative measures will contribute to maintaining your condition in a well-controlled state."

Summary of COPD zone calculation and action plan in *AIrway*.

Zone	Thresholds	CTS action plan
Red	• Symptoms are not better after taking your fare-up medicine for 48 hours <u>OR</u> • Experiencing very short of breath, nervous, confused and/or drowsy, and/ or have a chest pain <u>OR</u> • CAT > 20 <u>OR</u> • BCSS <5 <u>OR</u> • NRS <5 <u>OR</u> • Temperature < 0 °C or > 32 °C <u>OR</u> • Humidity < 10% and > 70% <u>OR</u> • AQHI > 7	• A message to the user: "You are in the Red Zone. This indicates an increased risk of a severe COPD exacerbation. If you believe this prediction is accurate, you should proceed to the nearest hospital for immediate medical attention. Failure to seek medical assistance within the next 15 minutes may escalate the likelihood of a significant COPD exacerbation."
Yellow	• Changes in sputum for at least 2 days <u>OR</u> • More shortness of breath than usual for at least 2 days <u>OR</u> • CAT score between 10-20 <u>OR</u> • BCSS <5 <u>OR</u> • NRS <5	• A message to the user: "You are in the Yellow Zone. If you believe this prediction is accurate, you should incorporate prescribed medications or COPD flare-up medications into your routine as directed by your healthcare provider. Please pay attention

		to the temperature, humidity, and pollen levels in your area. If your doctor has provided specific breathing and relaxation methods, now is the time to implement them.”
Green	• No color change in sputum OR • CAT < 10 OR • BCSS <5 OR • NRS <5	• A message to the user: “You are in the Green Zone. It's important to maintain this status. If you believe this prediction is accurate, you should continue taking your prescribed daily puffers to support your respiratory health. Additionally, be proactive in avoiding triggers that may worsen your condition. Consistent adherence to your treatment plan and preventative measures will contribute to maintaining your condition in a well-controlled state.”

Appendix V: uMARS questionnaire

SECTION A: Engagement

1. Is the app fun/entertaining to use?

a. Dull, not fun or entertaining at all
b. Mostly boring
c. OK, fun enough to entertain user for a brief time (< 5 minutes)
d. Moderately fun and entertaining, would entertain user for some time (5-10 minutes total)
e. Highly entertaining and fun, would stimulate repeat use

2. Is the app interesting to use?

a. Not interesting at all
b. Mostly uninteresting
c. OK, neither interesting nor uninteresting; would engage the user for a brief time (< 5 minutes)
d. Moderately interesting; would engage the user for some time (5-10 minutes total)
e. Very interesting, would engage the user in repeat use

3. What do you think of the app content?

a. Completely inappropriate, unclear or confusing
b. Mostly inappropriate, unclear or confusing
c. Acceptable but not specifically designed for the target audience. May be inappropriate, unclear or confusing at times
d. Designed for the target audience, with minor issues
e. Designed specifically for the target audience, no issues were found

4. Do you want to provide more details about app engagement?

____

SECTION B: Functionality-

5. For the home screen, how accurately is the information displayed (e.g., weather, information, location and time)?

a. The display is insufficient/inaccurate (e.g., crashes/broken features, etc.)
b. The display works, but lagging or contains major technical problems
c. The function works overall. Some technical problems need fixing/slow at times
d. Mostly functional with minor/negligible problems
e. Perfect display. No technical bugs found

6. For the home screen, are the buttons and menu fast and responsive?

a. The buttons/menu is broken and there is no/insufficient/inaccurate response (e.g., crashes/broken features, etc.)
b. The buttons/menu works, but lagging or contains major technical problems
c. The buttons/menu works overall. Some technical problems need fixing/slow at times
d. Mostly functional with minor/negligible problems
e. Perfect response. No technical bugs found

7. Is the app easy to use? Are the menus and instructions clear? Are the labels and icons helpful?

a. No/limited instructions; menu labels/icons are confusing; complicated
b. Takes a lot of time or effort
c. Takes some time or effort
d. Easy to learn (or has clear instructions)
e. Able to use the app immediately; intuitive; simple (no instructions needed)

8. Is login/ register a user account uninterrupted?

a. The navigation is difficult
b. Usable after a lot of time/effort
c. Usable after some time/effort
d. Easy to use
e. Perfectly logical, easy, clear flow throughout

9. Are interactions (taps/scrolls) consistent and intuitive across all screens?

a. Completely inconsistent/confusing
b. Often inconsistent/confusing
c. OK with some inconsistencies/confusing elements

d. Mostly consistent/intuitive with negligible problems
e. Perfectly consistent and intuitive

10. Do you want to provide more details about app functionality?

____

SECTION C: Aesthetics

11. Is the arrangement and size of buttons/icons on the screen appropriate?

a. Very bad design, cluttered, some options impossible to select, locate, see or read
b. Bad design, random, unclear, some options difficult to select, locate, see or read
c. Satisfactory, few problems with selecting, locating, seeing or reading items
d. Mostly clear, able to select, locate, see or read items
e. Professional, simple, clear, orderly, logically organized

12. How high is the quality of graphics used for the content?

a. Graphics appear amateur, very poor visual design – completely stylistically inconsistent
b. Low-quality graphics or low-quality visual design – stylistically inconsistent
c. Moderate quality graphics and visual design – generally consistent in style
d. High-quality graphics and visual design – mostly stylistically consistent
e. Very high-quality graphics and visual design – stylistically consistent throughout

13. How does the app look on the screen?

a. Ugly, unpleasant to look at, poorly designed, clashing, mismatched colors
b. Bad – poorly designed, bad use of color, visually boring
c. OK – average, neither pleasant, nor unpleasant
d. Pleasant – seamless graphics – consistent and professionally designed
e. Beautiful – very attractive, memorable, stand out; use of color enhances app features/menus

14. Do you want to provide more details about app aesthetics?

____

SECTION D: Information

15. Is the weather data relevant to the app?

a. Irrelevant, inappropriate, incoherent or incorrect
b. Poor. Barely relevant, appropriate, coherent, or may be incorrect
c. Moderately relevant, appropriate, coherent, or appears correct
d. Relevant, appropriate, coherent, correct

e. Highly relevant, appropriate, coherent, or correct

16. Is the clinical diary relevant to the app?

a. Irrelevant**,** inappropriate, incoherent or incorrect
b. Poor. Barely relevant, appropriate, coherent, or may be incorrect
c. Moderately relevant, appropriate, coherent**,** or appears correct
d. Relevant**,** appropriate, coherent, correct
e. Highly relevant, appropriate, coherent, or correct

17. Does the help page provide clear, logical, and correct information?

a. Completely unclear, confusing, wrong
b. Mostly unclear, confusing, or wrong
c. OK but often unclear, confusing, or wrong
d. Mostly clear, logical, or correct with negligible issues
e. Perfectly clear, logical, or correct

18. Does the error messaging provide clear, logical, and correct information?

a. Completely unclear, confusing, wrong
b. Mostly unclear, confusing, or wrong
c. OK but often unclear, confusing, or wrong
d. Mostly clear, logical, or correct with negligible issues
e. Perfectly clear, logical, or correct

19. Do you want to provide more details about app information?

____

SECTION E: App subjective quality

20. Do you think the app can be used for self-management purpose (e.g., used by patients daily for monitoring their health conditions)?

a. The app has no chance of achieving it
b. The app has very little chance of achieving it
c. This app may be able to achieve it
d. This app has high chance of achieving it

21. Would you pay for this app?

a. No
b. Maybe
c. Yes

22. What is your overall star rating of the app?

a. 1 star
b. 2 stars
c. 3 stars
d. 4 stars
e. 5 stars

23. Would you make changes or add anything to this app? If yes, please describe it below.

____

Appendix VI: IQVIA questionnaire

Please answer the following questions. If you believe the function is presented in the app, please select “Yes”. If not, please select “No”.

Rating description	User Response
1. Provide information in a variety of formats (e.g., text, photo, video)	
2. Provide instructions to the user (e.g., app user guide)	
3. Capture user-entered data (e.g., diary response)	
4. Able to enter and store health data on the individual’s phone	
5. Able to transmit health data (e.g., export, upload, email data)	
6. Able to evaluate the entered data by patient and provider, provider and administrator, or patient and caregiver	
7. Able to send alerts based on the data collected or propose behavioral intervention or changes (e.g., self-management action)	
8. Graphically display user-entered data/ output user-entered data	
9. Provide guidance based on user-entered information, and may further offer a diagnosis, or recommend a consultation with a physician/ a course of treatment	
10. Provide reminders to the user	
11. Provide communication between health care providers, patients, consumers, and caregivers and/ or provide links to social networks	

Appendix VII: Accessibility analysis on *AIrway* app interfaces

User Interfaces	Accessibility Scanner Results
Login	The "*New User? Register*" and "*Forgot Password? Click Here*" text views currently have fixed widths and scalable text. It's recommended to adjust the layout settings to allow for text expansion, such as using $wrap_{content}$. The input item height for "*Email*" and "*Password*" is currently 44dp. Consider increasing the height of this target to 48dp or larger.
Forgot Password Popup	The input item height for "*Reset Password*" is currently 40dp. Consider increasing the height of this target to 48dp or larger.
Register	The input item height for "*Full Name,*" "*Email,*" and the selection input for "*What Condition Do You Want to Manage*" is currently 44dp. Consider increasing the height of these touch targets to 48dp or larger.
Tell Us More About You	The selection item for the user's "*Sex*" and units for "*kg,*" "*lbs,*" "*m,*" and "*ft*" input is currently set at 24dp. Consider increasing the height of this target to 48dp or larger. The input item height for "*Weight*" and "*Height*" is currently 40dp. Consider increasing the height of these targets to 48dp or larger.
Medication	The selection item for "*Medication,*" "*Amount,*" and "*Frequency*" input is currently 24dp. Consider increasing the height of this target to 48dp or larger.
Diary Reminder	Consider increasing the current contrast ratio (3.80:1) to a higher ratio (e.g., 4.50:1) between the unselected time-scrolling texts (light grey color) and the app background (blue color).
Clinical Diary Questionnaires	The selection item for the questionnaire input is currently 32dp. Consider increasing the height of this target to 48dp or larger.
Today Page	Consider increasing the current contrast ratio (2.34:1) to a higher ratio (e.g., 3.00:1) between the "Today" icon (green color) and the selection menu background (light grey color). The "*System Monitoring*" and "*Recommended Action*" text views currently have fixed widths and scalable text. It's recommended to adjust the layout settings to allow for text expansion, such as using $wrap_{content}$.

Report Page	Consider increasing the current contrast ratio (2.34:1) to a higher ratio (e.g., 3.00:1) between the "*Report*" icon (green color) and the selection menu background (light grey color).
Profile Page	Consider increasing the current contrast ratio (2.34:1) to a higher ratio (e.g., 3.00:1) between the "*Profile*" icon (green color) and the selection menu background (light grey color). The explainable view list has fixed widths and scalable text. It's recommended to adjust the layout settings to allow for text expansion, such as using $wrap_{content}$.
Help Page	Consider increasing the current contrast ratio (2.34:1) to a higher ratio (e.g., 3.00:1) between the "*Help*" icon (green color) and the selection menu background (light grey color). The explainable view list has fixed widths and scalable text. It's recommended to adjust the layout settings to allow for text expansion, such as using $wrap_{content}$.

Appendix VIII: Open-ended question responses of technical raters

Do you want to provide more details about app engagement?
Feedback #1: Most functionalities are correctly implemented
Feedback #2: It was a nice app meets the users' needs. There might still need to be a few UI tweaks like spacing and font sizes. Also, the email input in the forgot password popup is not very intuitive, it would be nice to have an input box similar to the email input box on the login page with proper labeling. Also, when the yes button is clicked it would be nice to show an error message asking to input email rather than just closing the app.
Feedback #3: The first question asks about whether the app was fun/entertaining - I guess I never thought about the app as having to be that way. So my selection of "mostly boring" is not a bad thing, i.e. doesn't give a negative connotation to the app. For me a "fun" app would be gamified or with more interactive elements, but I would not expect that from a medical related app anyway. In terms of engagement, the notification helps to stay engaged, although I wish it would automatically dismiss once I clicked "Complete" and was redirected to the diary entry.
Feedback #4: The font size at the top of the app was quite large and it made viewing the temperature information difficult. I didn't know I can click on the information icon and additional information popped up. I wouldn't have done this if I did not receive the instructions. The interface of the app doesn't look very enticing to the user, no color was used other than the report page.
Feedback #5: Very effective and informative. Could possibly benefit from and slightly more varied colour pallet. Today screen could be benefit from minor images or icons.
Do you want to provide more details about app functionality?
Feedback #6: I think there should be a nice way to distinguish between the page titles and content. Also, it's need more spacing in a few places for example my link to call emergency contact was kind of cut off and there was no space between temperature content and humidity content.
Feedback #7: Would be great to have a "View your password" especially when creating a new account to make sure my spellings are correct. I spent a couple of times trying to set the passwords because both of them were not matching. Labels on the bottom navigation icons would be helpful on hover/click (e.g., it only said "Today" some time if I remember correctly, but not when I initially opened the app). It took me a minute to realize the second icon is a report, I thought it was a diary entry/notebook icon.

The reset password is a bit unintuitive - I clicked yes without typing in an email/password thinking that it would then take me to the next page where I could reset my password (that made the app crash though). So maybe having a textbox instead of an underline would make it clear that the user is expected to put in the email there. Overall, pretty simple app with no complex navigation required!
Feedback #8: I think the interactions across different screens can be difficult among older adults that are not used to using mobile apps and phones. The font was relatively large, it would be better if there was an option to decrease the font size. Login page was smooth and easy to use.
Feedback #9: Fairly smooth. Menu buttons are responsive and point the appropriate info.
Do you want to provide more details about app aesthetics?
Feedback #10: The display is a bit wordy, more graphical icons can be used in placed of text
Feedback #11: For the things like temperature, humidity, PM10, PM2.5 they seem all clustered together for some reason. I feel icons or smaller text might actually do the trick. And for the tab bar on the bottom if there could be more spacing between the texts and the icons on the active screen it would look nicer.
Feedback #12: Forgot to mention previously that it wasn't clear what was clickable and what isn't - maybe highlighting that in some way would help. Also, I prefer if previous toggles are closed when new toggles are opened (e.g., in the FAQ and Privacy Policy), but that is my personal preference, and I'm nit-picking here.
Feedback #13: The quality of the graphics was not too high; the font was clear though and easy to understand. I think the app can look better with smaller font size and more colour on the first screen.
Feedback #14: Graphics seem alright, but layout needs to be optimized. Some overlap of text especially on Today screen.
Do you want to provide more details about app information?
Feedback #15: I feel on the help page "support" should a bigger font since it is the main title.
Feedback #16: I find the weather-related information somewhat redundant because an Android phone user could just have a weather app for that information. Probably if this provided more illness-specific details, e.g., percentage of pollen in the air, recommendation for how to protect oneself in the current weather, etc. that might be very useful. The error for resetting password was unclear (the App crashed instead of redirecting me to type out the associated email).
Feedback #17: The weather app is relevant for asthma. The diary page was easy to use and the prompt worked well to remind me to complete it. The FAQ and error messaging was clear,

no issues.
Feedback #18: App seems very functional, minor layout and format adjustments should seem to be only issues so far.
Would you make changes or add anything to this app? If yes, please describe it below.
Feedback #19: Nice app overall. Love the concept!
Feedback #20: I guess a feature on how often to fill in the diary entry would help (e.g., how many times a day daily), based on the needs of the user.
Feedback #21: I would add the pollen levels and air quality to the app so patients can understand more about the weather prior to stepping outside. I think the interface can be more esthetically pleasing with more colours and font changes. If the app was recommended by a healthcare provider, I think some patients will be open to trying it. I don't think people would use it if they had to pay for it.
Feedback #22: Add a few more graphics to engage the user more and simple optimization; format and layout issues, mainly on Today screen, some texts got cut out. Would be good to have a history of symptoms.

Reference

1. Wu C-T, Li G-H, Huang C-T, et al. Acute exacerbation of a chronic obstructive pulmonary disease prediction system using wearable device data, machine learning, and deep learning: development and cohort study. *JMIR mHealth and uHealth*. 2021;9(5):e22591.
2. Rowland SP, Fitzgerald JE, Holme T, Powell J, McGregor A. What is the clinical value of mHealth for patients? *NPJ digital medicine*. 2020;3(1):1-6.
3. Kadambi P, Mohanty A, Ren H, et al. Towards a wearable cough detector based on neural networks. IEEE; 2018:2161-2165.
4. Wu Y, Li F, Xie Y, Wang Y, Yang Z. SymListener: detecting respiratory symptoms via acoustic sensing in driving environments. *ACM Transactions on Sensor Networks*. 2023;19(1):1-21.
5. Sun X, Lu Z, Hu W, Cao G. SymDetector: detecting sound-related respiratory symptoms using smartphones. 2015:97-108.
6. Lei Z, Martignetti L, Ridgway C, Peacock S, Sakata JT, Li-Jessen NY. Wearable neck surface accelerometers for occupational vocal health monitoring: instrument and analysis

validation study. *JMIR Formative Research*. 2022;6(8):e39789.
7. Zanartu M, Ho JC, Kraman SS, Pasterkamp H, Huber JE, Wodicka GR. Air-borne and tissue-borne sensitivities of bioacoustic sensors used on the skin surface. *IEEE Transactions on Biomedical Engineering*. 2008;56(2):443-451.
8. Mehta DD, Zanartu M, Feng SW, Cheyne II HA, Hillman RE. Mobile voice health monitoring using a wearable accelerometer sensor and a smartphone platform. *IEEE Transactions on Biomedical Engineering*. 2012;59(11):3090-3096.
9. Groh R, Lei Z, Martignetti L, Li-Jessen NY, Kist AM. Efficient and explainable deep neural networks for airway symptom detection in support of wearable health technology. *Advanced Intelligent Systems*. 2022;4(7):2100284.
10. Lei Z, Kennedy E, Fasanella L, Li-Jessen NY, Mongeau L. Discrimination between Modal, Breathy and Pressed Voice for Single Vowels Using Neck-Surface Vibration Signals. *Appl Sci (Basel)*. Apr 2019;9(7)doi:10.3390/app9071505
11. Song Y, Yun I, Giovanoli S, Easthope CA, Chung Y. Multimodal deep ensemble classification system with wearable vibration sensor for detecting throat-related events. *npj Digital Medicine*. 2025;8(1):14.
12. Kang YJ, Arafa HM, Yoo J-Y, et al. Soft skin-interfaced mechano-acoustic sensors for real-time monitoring and patient feedback on respiratory and swallowing biomechanics. *NPJ digital Medicine*. 2022;5(1):147.
13. Lee HK, Park SU, Kong S, et al. Real-time deep learning-assisted mechano-acoustic system for respiratory diagnosis and multifunctional classification. *npj Flexible Electronics*. 2024;8(1):69.
14. Ventola CL. Mobile devices and apps for health care professionals: uses and benefits. *P T*. May 2014;39(5):356-64.
15. Mehta DD, Van Stan JH, Hillman RE. Relationships between vocal function measures derived from an acoustic microphone and a subglottal neck-surface accelerometer. *IEEE/ACM transactions on audio, speech, and language processing*. 2016;24(4):659-668.
16. Vijayan V, Connolly JP, Condell J, McKelvey N, Gardiner P. Review of wearable devices and data collection considerations for connected health. *Sensors*. 2021;21(16):5589.
17. Ahmed A, Ali N, Aziz S, et al. A review of mobile chatbot apps for anxiety and depression and their self-care features. *Computer Methods and Programs in Biomedicine Update*. 2021;1:100012.
18. Liang Z, Tatha O, Andersen LE. Developing mHealth app for tracking academic stress and physiological reactions to stress. IEEE; 2020:147-150.
19. Beierle F, Allgaier J, Stupp C, et al. Self-assessment of having covid-19 with the corona check mhealth app. *IEEE Journal of Biomedical and Health Informatics*. 2023;27(6):2794-2805.
20. Griffin L, Lee D, Jaisle A, et al. Creating an mHealth app for colorectal cancer screening: user-centered design approach. *JMIR human factors*. 2019;6(2):e12700.
21. Giebel GD, Abels C, Plescher F, et al. Problems and Barriers Related to the Use of mHealth Apps From the Perspective of Patients: Focus Group and Interview Study. *Journal of Medical Internet Research*. 2024;26:e49982.
22. Apple. Apple Watch https://www.apple.com/ca/watch/. Accessed May 10 2023.
23. Fitbit. Fitbit Official Site for Activity Trackers & More. https://www.fitbit.com/global/en-ca/home. Accessed March 2 2022.
24. Bernbaum A. Afflo. https://www.annabernbaum.com/afflo. Accessed March 1, 2022.
25. Devani N, Pramono RXA, Imtiaz SA, Bowyer S, Rodriguez-Villegas E, Mandal S.

Accuracy and usability of AcuPebble SA100 for automated diagnosis of obstructive sleep apnoea in the home environment setting: an evaluation study. *BMJ open*. 2021;11(12):e046803.
26. Morita PP, Yeung MS, Ferrone M, et al. A patient-centered mobile health system that supports asthma self-management (breathe): design, development, and utilization. *JMIR mHealth and uHealth*. 2019;7(1):e10956.
27. Sonde. Unleash the power of voice as a vital sign. https://www.sondehealth.com. Accessed April 15 2023.
28. Hyfe. Harness the potential of cough as a vital sign. https://www.hyfe.ai. Accessed April 6, 2023.
29. Apple. Human Interface Guidelines. https://developer.apple.com/design/human-interface-guidelines. Accessed June 8, 2023.
30. Android. Typography. https://m1.material.io/style/typography.html#. Accessed June 8 2023.
31. Commission E. Green Paper on mobile Health (mHealth). https://digital-strategy.ec.europa.eu/en/library/green-paper-mobile-health-mhealth. Accessed June 30 2024.
32. Food&Drug US. Policy for Device Software Functions and Mobile Medical Applications. https://www.fda.gov/regulatory-information/search-fda-guidance-documents/policy-device-software-functions-and-mobile-medical-applications. Accessed June 30, 2024.
33. Society THIaMS. Xcertia mHealth App Guidelines. https://www.himss.org/sites/hde/files/media/file/2020/04/17/xcertia-guidelines-2019-final.pdf. Accessed May 25, 2024.
34. HHS USDoHaHS. Health App Use Scenarios & HIPAA. https://www.hhs.gov/sites/default/files/ocr-health-app-developer-scenarios-2-2016.pdf. Accessed August 5, 2024.
35. Llorens-Vernet P, Miró J. Standards for mobile health–related apps: systematic review and development of a guide. *JMIR mHealth and uHealth*. 2020;8(3):e13057.
36. Android. Create XML layouts for Android. https://developer.android.com/codelabs/basic-android-kotlin-training-xml-layouts#0. Accessed March 20 2023.
37. Android. Android Studio Chipmunk | 2021.2.1 (May 2022). https://developer.android.com/studio/releases/past-releases/as-chipmunk-release-notes. Accessed March 3 2023.
38. Morville P. User experience honeycomb. https://www.uxpin.com/studio/blog/ux-honeycomb-definition-and-use/. Accessed March 8, 2022.
39. Göransson C, Eriksson I, Ziegert K, et al. Testing an app for reporting health concerns—experiences from older people and home care nurses. *International journal of older people nursing*. 2018;13(2):e12181.
40. Creighton JR. Yogic Breathing for Post-Traumatic Stress Disorder: Designing an Application to Supplement Learning and Overcome a Stress State. 2014;
41. Vaghefi I, Tulu B. The continued use of mobile health apps: insights from a longitudinal study. *JMIR mHealth and uHealth*. 2019;7(8):e12983.
42. Caldwell B, Cooper M, Reid LG, et al. Web content accessibility guidelines (WCAG) 2.0. *WWW Consortium (W3C)*. 2008;290:1-34.
43. Android. Build a responsive UI with ConstraintLayout https://developer.android.com/develop/ui/views/layout/constraint-layout. Accessed March 3 2022.
44. Coolors. Color Contrast Checker. https://coolors.co/contrast-checker/112a46-acc8e5.

Accessed March 5, 2022.
45. AGWG AGWG. Understanding SC 1.4.6: Contrast (Enhanced) (Level AAA). https://www.w3.org/WAI/WCAG21/Understanding/contrast-enhanced.html. Accessed July 25 2024.
46. Android. Request location permissions. https://developer.android.com/training/location/permissions#approximate-request. Accessed March 05, 2023.
47. Android. DatePicker. https://developer.android.com/reference/android/widget/DatePicker. Accessed April 02 2023.
48. Long R. The Canadian Lung Association/Canadian Thoracic Society and tuberculosis prevention and control. *Canadian respiratory journal*. 2007;14(7):427-431.
49. Ontario TLA. Respiratory medications. Accessed May 10 2023. https://taddlecreekfht.ca/wp-content/uploads/2014/10/Respiratory-Medications.pdf
50. van Kruijssen V, van Staa A, Dwarswaard J, Mennema B, Adams SA. Use of online self-management diaries in asthma and COPD: a qualitative study of subjects' and professionals' perceptions and behaviors. *Respiratory care*. 2015;60(8):1146-1156.
51. O'Connell S, McCarthy VJ, Queally M, Savage E. The preferences of people with asthma or chronic obstructive pulmonary disease for self-management support: A qualitative descriptive study. *Journal of Clinical Nursing*. 2021;30(19-20):2832-2841.
52. Juniper E, O'byrne P, Guyatt G, Ferrie P, King D. Development and validation of a questionnaire to measure asthma control. *European respiratory journal*. 1999;14(4):902-907.
53. Reddel HK, Bateman ED, Becker A, et al. A summary of the new GINA strategy: a roadmap to asthma control. *European Respiratory Journal*. 2015;46(3):622-639.
54. Jones P, Harding G, Berry P, Wiklund I, Chen W, Leidy NK. Development and first validation of the COPD Assessment Test. *European Respiratory Journal*. 2009;34(3):648-654.
55. Gómez FP, Rodriguez-Roisin R. Global Initiative for Chronic Obstructive Lung Disease (GOLD) guidelines for chronic obstructive pulmonary disease. *Current opinion in pulmonary medicine*. 2002;8(2):81-86.
56. DeVries R, Kriebel D, Sama S. Validation of the breathlessness, cough and sputum scale to predict COPD exacerbation. *NPJ primary care respiratory medicine*. 2016;26(1):1-3.
57. Android. TimePicker. https://developer.android.com/reference/android/widget/TimePicker. Accessed May 20, 2023.
58. See KC, Phua J, Lim TK. Trigger factors in asthma and chronic obstructive pulmonary disease: a single-centre cross-sectional survey. *Singapore medical journal*. 2016;57(10):561.
59. Organization WH. What are the WHO Air quality guidelines? https://www.who.int/news-room/feature-stories/detail/what-are-the-who-air-quality-guidelines. Accessed March 5 2023.
60. Chen T, Wang K, Ma X, et al. Acute respiratory response to individual particle exposure (PM1. 0, PM2. 5 and PM10) in the elderly with and without chronic respiratory diseases. *Environmental Pollution*. 2021;271:116329.
61. Canada Go. Air Quality Health Index. https://www.canada.ca/en/environment-climate-change/services/air-quality-health-index/about.html#. Accessed May 10, 2024.
62. Education NA, Program P. Expert panel report 3 (EPR-3): guidelines for the diagnosis and management of asthma-summary report 2007. *The Journal of allergy and clinical immunology*. 2007;120(5 Suppl):S94-S138.
63. Canada Go. Personal Information Protection and Electronic Documents Act (S.C. 2000, c. 5). https://laws-lois.justice.gc.ca/eng/acts/p-8.6/. Accessed May 12, 2023.

64. Quebec P. Act respecting the protection of personal information in the private sector. https://www.legisquebec.gouv.qc.ca/en/document/cs/p-39.1. Accessed May 13, 2023.
65. Google. Firebase Firestore. https://firebase.google.com/docs/storage. Accessed February 2, 2023.
66. Google. HIPAA Compliance on Google Cloud Platform. https://cloud.google.com/security/compliance/hipaa. Accessed February 4 2023
67. Adamovic M. Readability Calculator. https://www.online-utility.org/english/readability_test_and_improve.jsp Accessed March 10, 2023.
68. DuBay WH. *Smart Language: Readers, Readability, and the Grading of Text*. ERIC; 2007.
69. Readable. Readability Formulas. https://readable.com/readability/flesch-reading-ease-flesch-kincaid-grade-level/. Accessed March 14 2023.
70. Readability. The Automated Readability Index (ARI). https://readabilityformulas.com/automated-readability-index.php. Accessed May 1, 2023.
71. W3C. Mobile Accessibility at W3C. https://www.w3.org/WAI/standards-guidelines/mobile/. Accessed June 28, 2022.
72. Di Gregorio M, Di Nucci D, Palomba F, Vitiello G. The making of accessible android applications: an empirical study on the state of the practice. *Empirical Software Engineering*. 2022;27(6):145.
73. Google. Accessibility Scanner. https://play.google.com/store/apps/details?id=com.google.android.apps.accessibility.auditor&hl=en_CA&gl=US. Accessed May 15 2024.
74. Android. Android Studio release notes. https://developer.android.com/studio/releases. Accessed March 3, 2023.
75. OpenWeather. Current weather and forecasts collection. https://openweathermap.org/price#current. Accessed May 14 2023.
76. Albaina IM, Visser T, Van Der Mast CA, Vastenburg MH. Flowie: A persuasive virtual coach to motivate elderly individuals to walk. IEEE; 2009:1-7.
77. Canada A. Living with asthtma and Air Quality Health Index https://asthma.ca/get-help/living-with-asthma/air-quality-health-index/#:~:text=The%20Air%20Quality%20Health%20Index,to%20participate%20in%20outdoor%20activities. Accessed May 11, 2024.
78. Han A, Deng S, Yu J, Zhang Y, Jalaludin B, Huang C. Asthma triggered by extreme temperatures: from epidemiological evidence to biological plausibility. *Environmental Research*. 2023;216:114489.
79. CDC CfDCaP. Asthma Action Plan. https://www.cdc.gov/asthma/action-plan/documents/asthma-action-plan-508.pdf. Accessed May 15, 2023.
80. Gift AG, Narsavage G. Validity of the numeric rating scale as a measure of dyspnea. *American Journal of Critical Care*. 1998;7(3):200-204.
81. CTS CTS. COPD action plan. Accessed June 11, 2023. https://cts-sct.ca/wp-content/uploads/2019/03/5491_THOR_COPDActionPlanUpdate_2019_Editable_Eng_v2.pdf
82. Varshney H, Allahloh AS, Sarfraz M. Iot based ehealth management system using arduino and google cloud firestore. IEEE; 2019:1-6.
83. Fornari G, Minato R, Pilotto G, Palazzi CE. Applying frugal innovation to humidity and temperature monitoring. 2020:12-17.

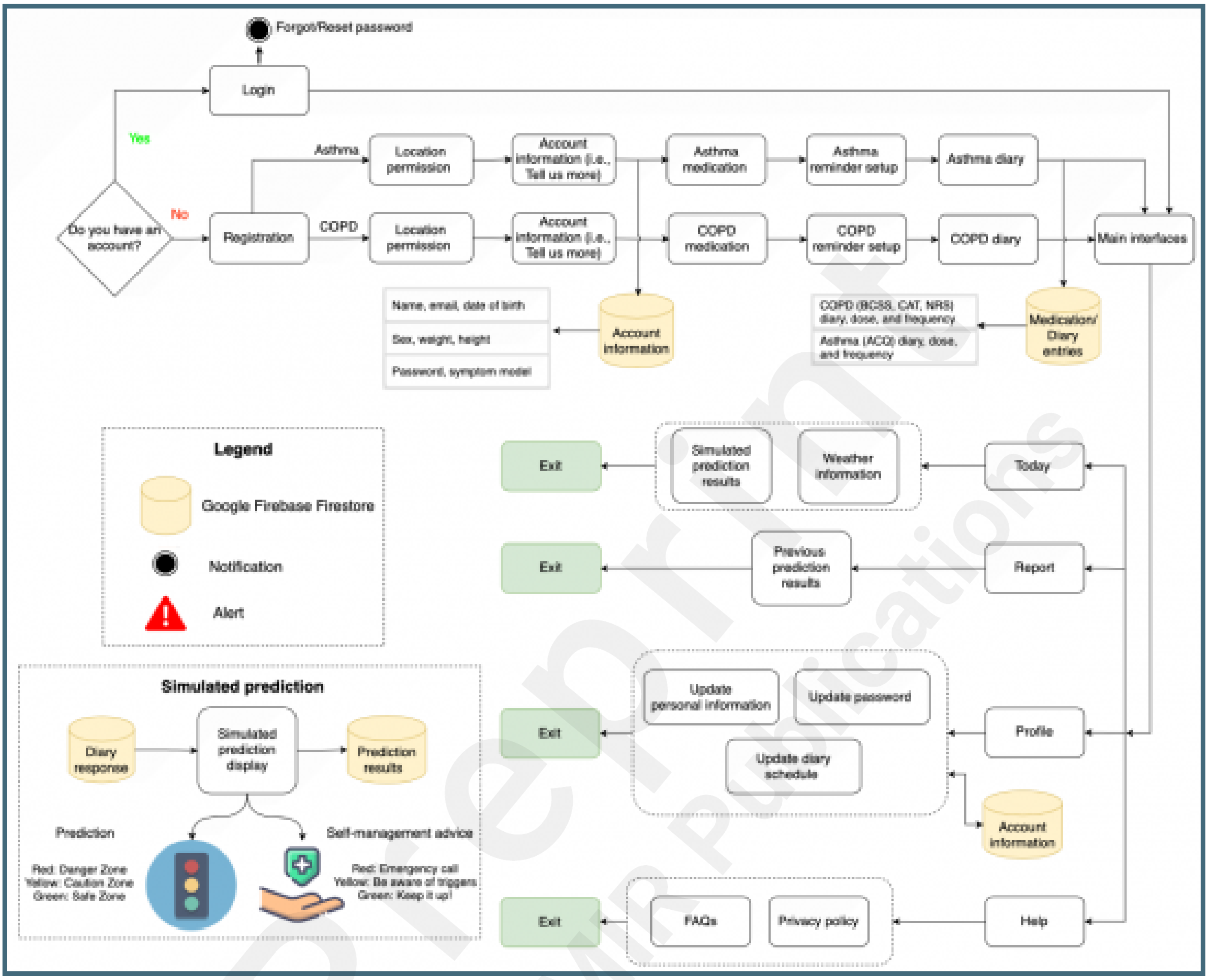
84. IBM. SQL vs. NoSQL Databases: What's the Difference? https://www.ibm.com/cloud/blog/sql-vs-nosql. Accessed June 1, 2023.
85. Chandra DG. BASE analysis of NoSQL database. *Future Generation Computer Systems*. 2015;52:13-21.
86. Sukmana Y, Rosmansyah Y. The Use of Cloud Firestore For Handling Real-time Data Updates: An Empirical Study of Gamified Online Quiz. IEEE; 2021:1239-1244.
87. Slingerland C. Horizontal Vs. Vertical Scaling: Which Should You Choose? https://www.cloudzero.com/blog/horizontal-vs-vertical-scaling/#:~:text=Horizontal%20scaling%20(aka%20scaling%20out,server%20may%20be%20your%20solution. Accessed Jul 31, 2024.
88. SIG B. Bluetooth Technology Overview. https://www.bluetooth.com/learn-about-bluetooth/tech-overview/. Accessed May 24, 2023.
89. Tosi J, Taffoni F, Santacatterina M, Sannino R, Formica D. Performance evaluation of bluetooth low energy: A systematic review. *Sensors*. 2017;17(12):2898.
90. Instruments T. CC2540 and CC2541 Bluetooth low energy Software Developer's Reference Guide. 2009.
91. Pc Os. BLE Protocol Stack — Controller. https://pcng.medium.com/ble-protocol-stack-controller-2d2d5371deec. Accessed December 18, 2022.
92. NovelBits. The Bluetooth Low Energy Protocol Stack: Understanding the layers. https://novelbits.io/bluetooth-low-energy-protocol-stack-layers/. Accessed December 14, 2022.
93. Oreilly. Chapter 4. GATT (Services and Characteristics). https://www.oreilly.com/library/view/getting-started-with/9781491900550/ch04.html. Accessed December 9, 2022.
94. Afaneh M. Bluetooth GATT: How to Design Custom Services & Characteristics. https://www.novelbits.io/bluetooth-gatt-services-characteristics/. Accessed December 15, 2022.
95. Firebase. Firebase Authentication. https://firebase.google.com/docs/auth. Accessed May 16, 2023.
96. Firebase. Authenticate with Firebase using Password-Based Accounts on Android. https://firebase.google.com/docs/auth/android/password-auth. Accessed May 16, 2023.
97. Firebase. Add data to Cloud Firestore. https://firebase.google.com/docs/firestore/manage-data/add-data. Accessed May 16, 2023.
98. Android. String resources. https://developer.android.com/guide/topics/resources/string-resource. Accessed May 18, 2023.
99. Android. TextView https://developer.android.com/reference/android/widget/TextView. Accessed May 18, 2023.
100. Ong CY. The Ultimate Guide to Android Bluetooth Low Energy. https://punchthrough.com/android-ble-guide/. Accessed December 10, 2022.
101. Documentation AD. Bluetooth Low Energy. https://developer.android.com/guide/topics/connectivity/bluetooth/ble-overview. Accessed June 2 2023.
102. Developers A. BluetoothLeScanner. May 5, 2023 https://developer.android.com/reference/android/bluetooth/le/BluetoothLeScanner
103. Developers A. BluetoothDevice. https://developer.android.com/reference/android/bluetooth/BluetoothDevice. Accessed June 2, 2023.
104. Developers A. BluetoothGatt. https://developer.android.com/reference/android/bluetooth/BluetoothGatt. Accessed June 2, 2023.

105. Semiconductor N. nRF52840 DK. https://www.nordicsemi.com/Products/Development-hardware/nrf52840-dk. Accessed June 5 2023.
106. Stoyanov SR, Hides L, Kavanagh DJ, Wilson H. Development and validation of the user version of the Mobile Application Rating Scale (uMARS). *JMIR mHealth and uHealth*. 2016;4(2):e5849.
107. Choi YK, Demiris G, Lin S-Y, et al. Smartphone applications to support sleep self-management: review and evaluation. *Journal of Clinical Sleep Medicine*. 2018;14(10):1783-1790.
108. Schmeelk S, Davis A, Li Q, et al. Monitoring symptoms of COVID-19: review of mobile apps. *JMIR mHealth and uHealth*. 2022;10(6):e36065.
109. LimeSurvey. LimeSurvey (No.3). https://community.limesurvey.org/. Accessed April 10, 2023.
110. Firebase G. Firebase App Distribution. https://firebase.google.com/docs/app-distribution. Accessed May 6, 2023.
111. Calculator C. Flesch Reading Ease. https://charactercalculator.com/flesch-reading-ease/. Accessed June 10, 2023.
112. Readable. What is a Gunning Fog Index readability score? https://readable.com/readability/gunning-fog-index/. Accessed March 14 2023.
113. Readable. The Coleman Liau Readability Index. Accessed March 14 2023. https://readable.com/readability/coleman-liau-readability-index/
114. Readable. Flesch-Kincaid Grade Level. https://readable.com/readability/flesch-reading-ease-flesch-kincaid-grade-level/#:~:text=The%20Flesch%2DKincaid%20Grade%20Level%20is%20equivalent%20to%20the%20US,schooling%20age%2013%20to%2014. Accessed March 14, 2023.
115. Readability. The SMOG Readability Formula. https://readabilityformulas.com/smog-readability-formula.php. Accessed May 01, 2023.
116. Readability. Readability Formulas. https://readabilityformulas.com/aboutus.php. Accessed May 01 2023.
117. metageek. Understanding RSSI. https://www.metageek.com/training/resources/understanding-rssi/
118. Sunjaya AP, Sengupta A, Martin A, Di Tanna GL, Jenkins C. Efficacy of self-management mobile applications for patients with breathlessness: Systematic review and quality assessment of publicly available applications. *Respiratory Medicine*. 2022:106947.
119. Diaz-Skeete YM, McQuaid D, Akinosun AS, Ekerete I, Carragher N, Carragher L. Analysis of apps with a medication list functionality for older adults with heart failure using the mobile app rating scale and the IMS institute for healthcare informatics functionality score: evaluation study. *JMIR mHealth and uHealth*. 2021;9(11):e30674.
120. Balebako R, Marsh A, Lin J, Hong JI, Cranor LF. The privacy and security behaviors of smartphone app developers. 2014;
121. Fuller-Tyszkiewicz M, Richardson B, Klein B, et al. A mobile app–based intervention for depression: End-user and expert usability testing study. *JMIR mental health*. 2018;5(3):e9445.
122. Marzuki MFM, Yaacob NA, bin Yaacob NM, Hassan MRA, Ahmad SB. Usable mobile app for community education on colorectal cancer: development process and usability study. *JMIR human factors*. 2019;6(2):e12103.
123. Flutter. Build apps for any screen. https://flutter.dev. Accessed August 5, 2024.

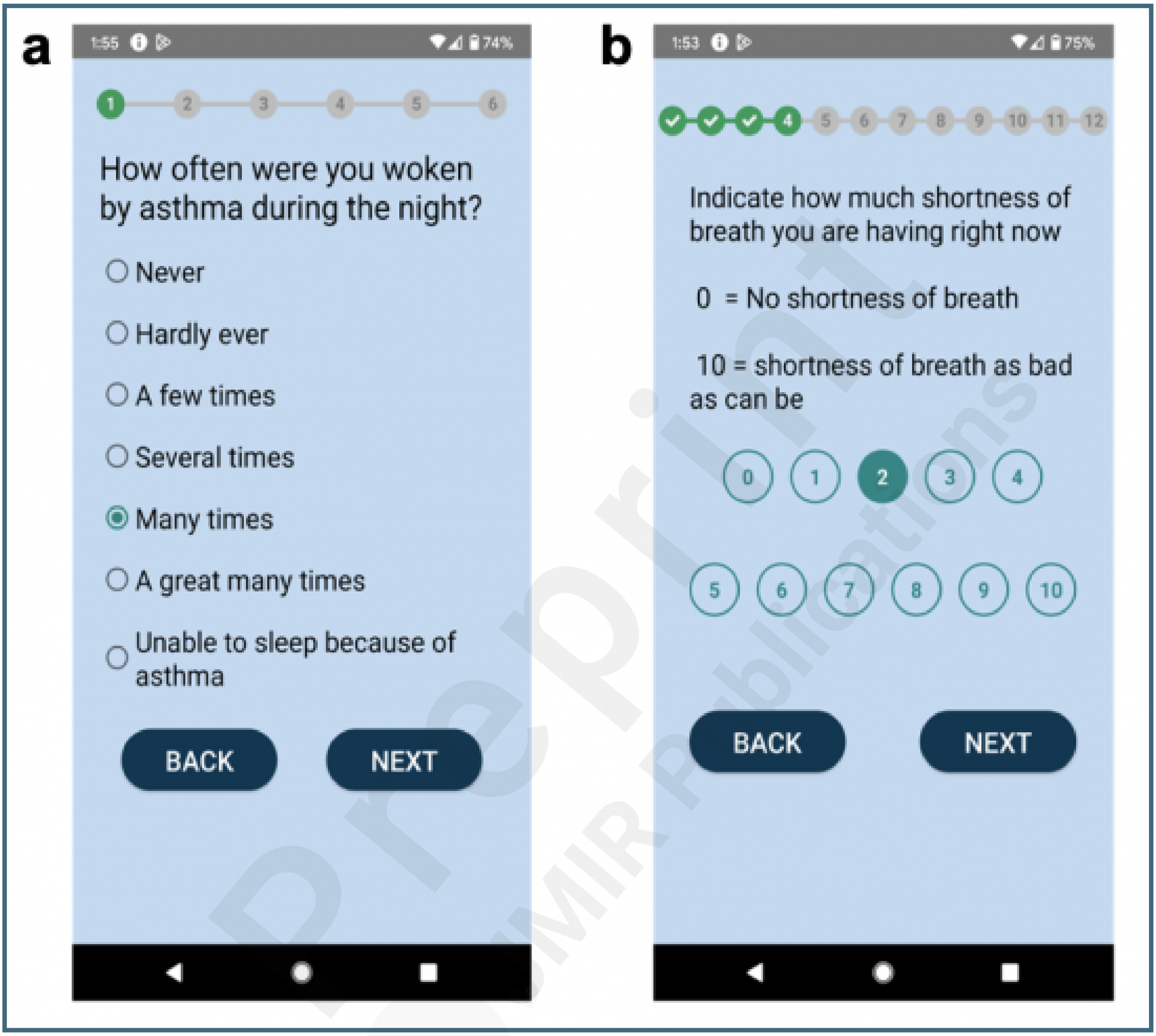
Supplementary Files

Figures

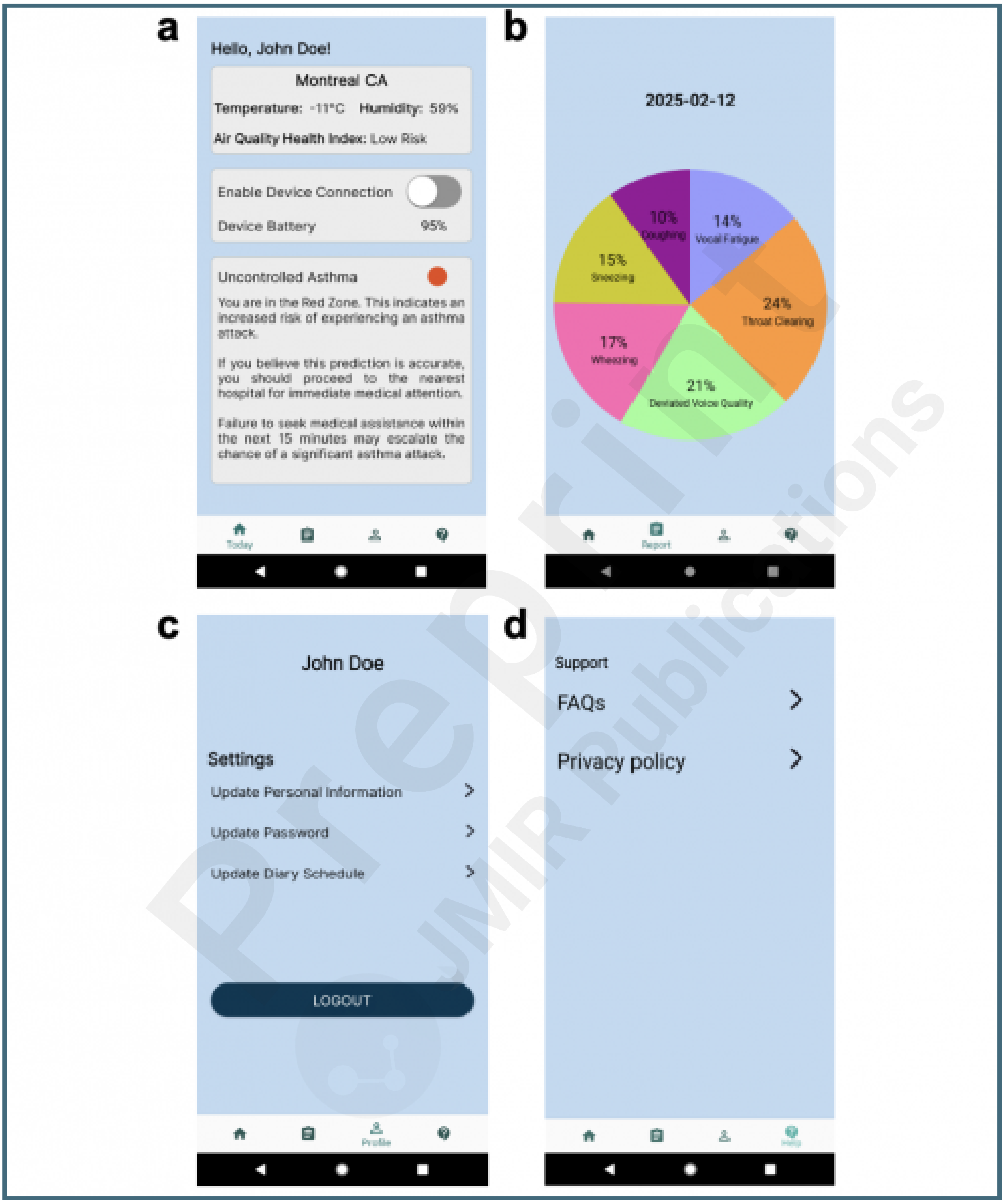
AIrway design flowchart.



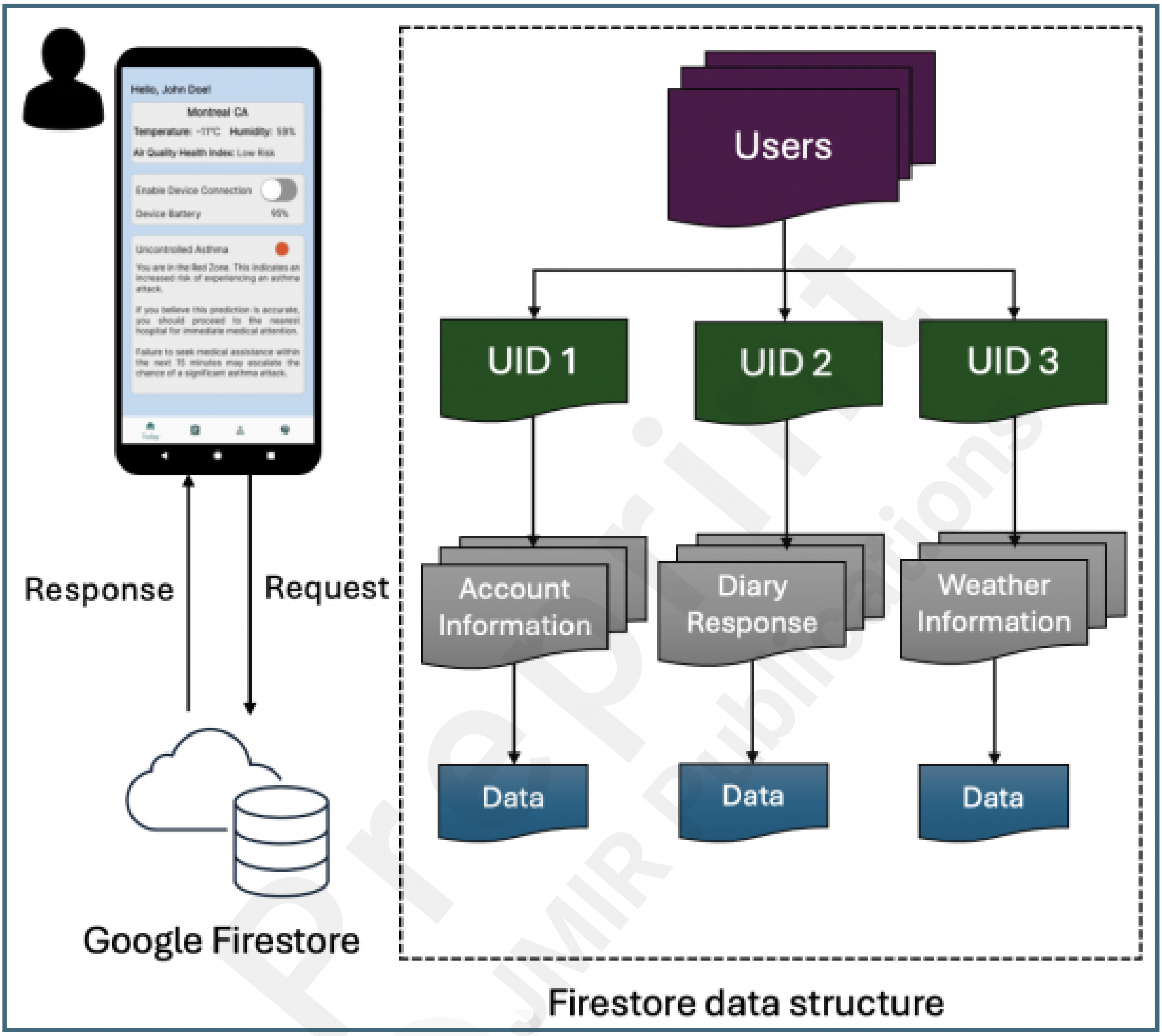
a) An ACQ question is presented in the asthma diary interface b) The NRS question is presented in the COPD diary interface.



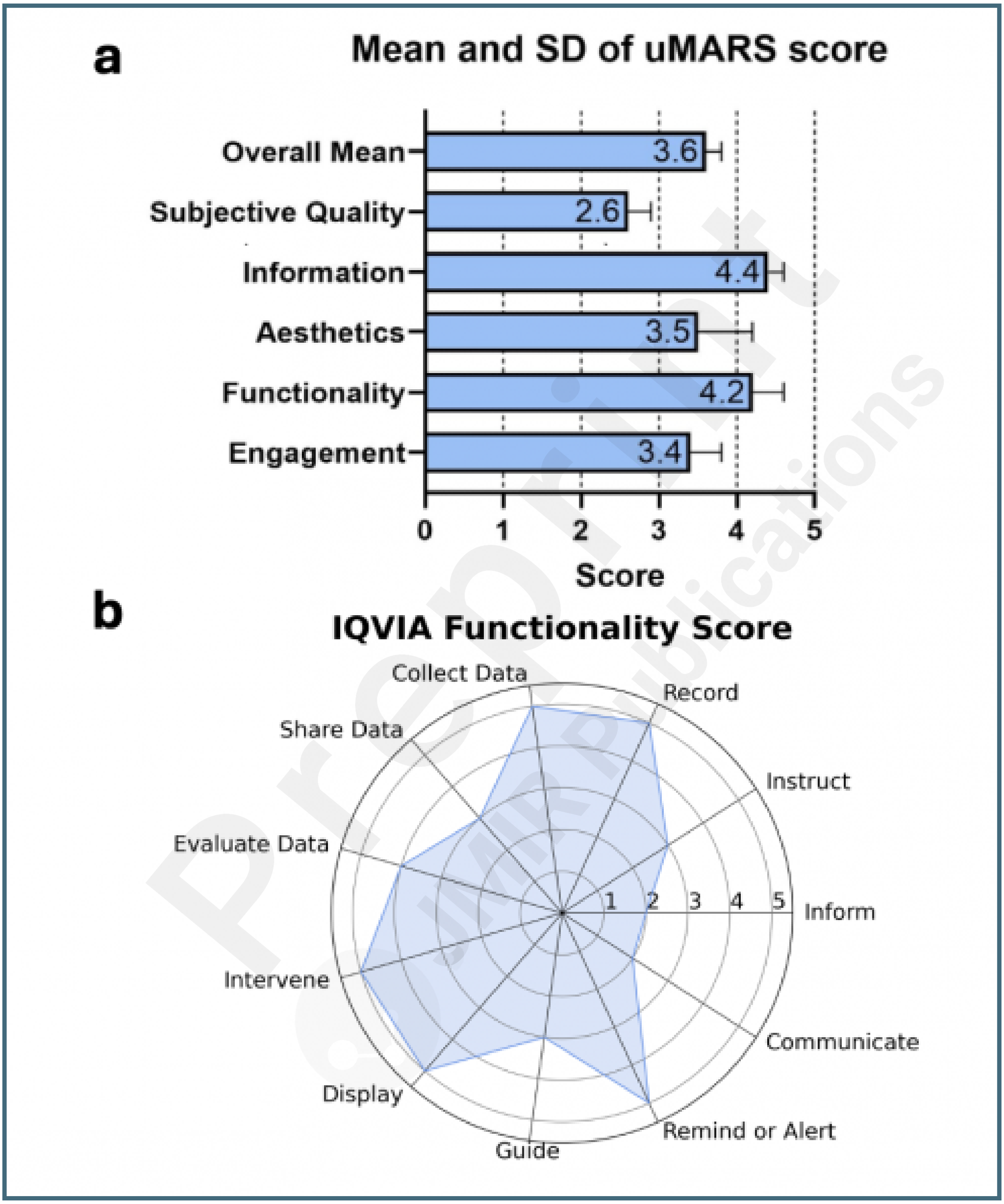
a) Today interface b) Report interface c) Profile interface d) Help interface.



Firestore cloud architecture and data flow of AIrway.



a) Technical raters' means and standard deviations (SD) of uMARS, and b) technical raters' IQVIA functionality scores (N=5).



Multimedia Appendixes

Supplementary Files.
URL: http://asset.jmir.pub/assets/74a85c9808a559814b5fa4de847abbbd.docx